L. C. Graton.

IGNEOUS ROCKS AND THEIR ORIGIN

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McGRAW-HILL BOOK COMPANY, INC.
239 WEST 39TH STREET, NEW YORK
6 BOUVERIE STREET, LONDON, E.C.
1914

Mount Baker (10,827 Feet) from the Fraser River at Mission Junction, 32 Miles Distant. The Volcano stands upon the Cascade Range Complex of folded Sediments, Ancient Volcanics, and Granitic Batholiths. Photograph by Canadian Pacific Railway Company.

IGNEOUS ROCKS

AND

THEIR ORIGIN

BY

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THE · MAPLE · PRESS · YORK · PA

To my Wife
Inspiring Fellow Worker
This Book is Dedicated

PREFACE

This book gives the substance of a course of lectures prepared for students in Harvard University and in the Massachusetts Institute of Technology. Its writing was begun at the Institute and finished at the University. The preliminary work that led the writer into the igneous-rock field was a study of Mount Ascutney, Vermont, twenty years ago. The fundamental problems in that small area are largely identical with those encountered outdoors during each succeeding field season. An attempt at their partial solution became more hopeful as facts were accumulated, both from rocks themselves and from the literature of geology. The last decade has been specially prolific in publications affecting the philosophy of eruptive rocks. Many of these recent memoirs have described definite proofs of vital principles which had been no more than suggested as possibilities during the preceding century. The combination of established principles, new and old, has led to the following general explanation of igneous activity. It is offered as a working hypothesis, which may have value in helping to indicate the truly important problems among the infinite number of those still unsolved. The history of science shows that it is generally harder to ask a significant question than to answer an insignificant question; and that in the bettering of working hypotheses the truth is approached.

At intervals since 1897 the writer has published on special igneous-rock themes. In a few instances the matter of such papers, after revision, has been incorporated in this book. In preparing those original papers as well as the material here published for the first time, much assistance has been given by colleagues in the Massachusetts Institute of Technology—Professors W. C. Bray, T. A. Jaggar, G. N. Lewis, A. A. Noyes, and C. H. Warren; and in Harvard University—Professors G. P. Baxter, P. W. Bridgman, H. N. Davis, L. S. Marks, C. Palache, T. W. Richards, and J. E. Wolff. The writer has profited from many discussions on the general subject with Professors A. C. Lane, F. D. Adams, and A. C. Lawson, and with Dr. F. E. Wright. Special acknowledgments are due to Dr. S. J. Schofield and Dr. J. A. Allan for unpublished information; to Mr. I. Friedlaender and Dr. A. Harker for permission to reproduce illustrations from their works; and to several publishers, especially Justus Perthes, Macmillan and

Company, The Macmillan Company, and U. Hoepli, for similar courtesies. In the actual preparation of the manuscript the writer is chiefly indebted to his wife, who performed much of the manual labor and, with rare tact and judgment, guided him through many a difficult passage in thought and expression.

CAMBRIDGE, MASSACHUSETTS,
July 25, 1913.

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INTRODUCTION

Geology has been charged with failure to measure up to the intellectual standard of the so-called "exact" sciences. The reproach is no longer merited. It originated during a century when the power of the experimental method in science was first clearly appreciated. As usually the case with great discoveries, this was soon given exaggerated importance by many students of the logic of science. Now that the intoxication of early, magnificent success in the use of experiment is succeeded by more sober second thought, it has become clearer that this method of research is only one of several that are quite essential and are of coordinate value in scientific thought. The incessant revision of experimental methods, and the inevitable shifts in the values credited to physical and chemical "constants," show the inexactness of the principal "exact" sciences. Their mathematics is precise; their premises are not. It is difficult to name a single experimental result which is not troubled with some degree of uncertainty. Nevertheless, using the principle of the limits of error, the principle of the compensation of errors, the principle of correlation, and the principle of direct inference, physics, chemistry, and astronomy have produced majestic and indispensable results. In each case, the fundamental unit of mass—molecule, atom, or star—can only be understood through the use of all these principles. At bottom each "exact" science is, and must be speculative, and its chief tool of research, too rarely used with both courage and judgment, is the regulated imagination.

Though not so tinctured with mathematics, geology is in essentially the same position. It is "exact" in the sense that a countless number of its observations are quantitative, with limits of error so small as to permit absolutely rigorous deduction. The larger part of the earth is inaccessible, like molecule, atom, or star, but the principle of inference has already afforded geological results which are as final, if not as fundamental, as those won in the other sciences. Many leading facts in geology have been necessarily secured through methods other than the experimental. The existence of peneplains has been proved in spite of the obvious impossibility of reproducing them in the laboratory or of reducing the subject of erosion to mathematical formulas. Some geologists refuse to consider seriously theoretical discussions regarding the earth's interior, on the ground that theory must await the quantitative data from the laboratory. This mental position is not justified by the master in physics, chemistry, or astronomy, whose imagination or speculative faculty is always working in advance of his "exact" determinations.

What geology, like every other science, needs to-day is a frank recognition that imaginative thought is not dangerous to science but is the life blood of science. Even the universities do not fully recognize this fact, and are notoriously failing to develop the stimuli which are necessary for the controlled, scientific imagination. Not only is geology now characterized by rigorous thought; by its nature as a science involving long excursions into space—inaccessible places—and time—epochs long passed—geology is peculiarly fitted to stimulate the regulated imagination, a process at the core of the highest education. Science is built on a long succession of mistakes. Their recognition has meant progress. Progress, indefinitely more rapid, will be possible when men of science have more generally lost the fear of making mistakes in using to the uttermost their powers of correlation and deduction. Science is drowning in facts. It can only be rescued by the growth of systems of thought. Better than none are "little systems" which "have their day and cease to be." We can hope that geology, like every other science, will find its superman who shall show us the building hidden behind the scaffolding of myriad isolated facts of nature. Meantime, it is the duty of every worker in science to strive for a complete mental system in his field of research and, however mistaken he may be, he should have the special sympathy of his fellows. The best sympathy is expressed in constructive criticism. The "facts" of to-day are the hypotheses of yesterday.

IGNEOUS ROCKS AND THEIR ORIGIN

CHAPTER I

ABSTRACT

A comprehensive knowledge of igneous rocks is important from many aspects. The sedimentary rocks could not much exceed a half-mile (0.8 km.) in average thickness if they were spread evenly over the earth. The stratified terranes themselves have been derived from igneous terranes. This planet is essentially a body of crystallized and uncrystallized igneous material. The final philosophy of earth history will therefore be founded on igneous-rock geology. The earth has the appearance of being a small, cooled star and its physical constitution and history are problems concerning the nearest of the stellar host. The formation of continental plateau, mountain range, or ocean basin is a product of forces developed in the planet below its pellicle of sediments. The salts of soil, river, and ocean waters, as well as organic matter and the gases of the atmosphere, are largely, if not wholly, derivatives of rock materials once in a state of fusion. It is becoming increasingly clear that most of the world's ore deposits are genetically connected with igneous rocks. Economic and dynamical geology, meteorology, climatology, and oceanography are thus deeply affected by increase of knowledge regarding the natural history of igneous rocks. Historical geology itself is enriched by a systematic review of the earth's eruptivity. Volcanic effusions and large-scale intrusions of granitic types of rock matter can often be used to date events directly registered in sedimentary formations.

This book is intended to summarize and correlate the facts known about igneous rocks, with special emphasis on their field relations. Knowledge of petrography and a moderate acquaintance with the physics and chemistry of rock-melts are assumed, but the treatment of the subject is essentially geological.

The work is divided into three parts. The first of these (Chapters II to VII inclusive) broadly considers the facts which need explanation in a philosophy of the igneous rocks. The second part (Chapters VIII to XIV inclusive) contains a general, eclectic theory on the sub-

seated solution of down-stoped blocks in batholithic magma, involving the necessity of belief in the secondary origin of much of the world's magmatic and igneous-rock matter.

Chapter XI is occupied with a theoretical study of magmatic assimilation in general. It is of two kinds, marginal and abyssal. The difficult problem of its quantitative importance is attacked and the conclusion drawn that no intrusive body is too large to be explained as the work of the primary basaltic wedge interacting on the two shells overlying the basaltic substratum.

Chapter XII is a general outline of the more important phases of magmatic differentiation. The mixed magmas due to assimilation ("syntectics") and, under certain conditions, the primary basalt itself are not stable solutions but break up into submagmas. These "non-consulute" fractions are segregated in two chief ways: usually by the direct action of gravity; and, on a much smaller scale, through the upward transfer of magmatic gases which have brought together silicate or oxide materials "entangled" with the rising gases. In general, the unit of differentiation is a small liquid mass and true fractional crystallization is regarded as a very subordinate mode of magmatic splitting. A general statement is given of demonstrated splitting in volcanic vents, sills, laccoliths, and batholiths. The most instructive illustration are those derived from sills and laccoliths, a number of which are tabulated, with concise statement of the facts.

Chapter XIII treats of the theory of volcanic action at central vents. Among the topics considered are: the localization and opening of the vent; the persistence of its eruptivity for long periods; the alternation of active and dormant stages; the rhythmic character of eruption during an active stage; the origin of the heat in the vent; the rate of heat-loss during activity; the principle of "two-phase convection," which is held to be the chief cause of the transfer of heat from the depths; the systematic changes during the life of a central vent, with respect to explosiveness and to the petrographic nature of its lavas; the origin of block lava and of ropy lava; the cause of lava outflow; the genetic classification of volcanic gases; the distinction between magmatic and phreatic explosions; and that between "principal" and "subordinate" volcanoes of the central type.

Chapter XIV summarizes the general theory, which is seen to be eclectic in character since it includes the ideas of many workers in petrogeny. The only other modern attempt to form a stable theory of approximately similar scope is that of Loewinson-Lessing, whose position is briefly discussed.

Chapter XV opens the third and concluding part of the volume.

The members of the gabbro clan are here listed and some of the more important are considered in their relation to the eclectic theory. The composition of the substratum basalt is approximately calculated, and in succession, the olivine-free basalts, the quartz diabases and their allies, the norites and related types, the hornblende gabbros, iron basalt, the anorthosites, and the pillow basalts and spilites are described in their genetic relations.

Chapter XVI discusses the granite clan. The origin of the granites is most clearly indicated by the facts known concerning many sills and laccoliths which have invaded sedimentary rocks. Assimilation combined with differentiation has there produced granitic types which are generally of somewhat abnormal composition. The abnormality is that expected by theory. The genesis of rocks showing the usual granitic composition has been considered in previous chapters. They are generally gravitative differentiates in gigantic abyssal wedges which are walled principally by the primitive acid earth-shell and are cross-cutting bodies, but otherwise are perfect homologues of large, more fully exposed laccoliths and sills. Many rocks of granitic composition (chemically speaking) are clearly differentiated from dioritic, granodioritic, syenitic, or monzonitic magmas. Gaseous transfer (pneumatolytic differentiation) is held responsible for the development of certain small-scale bodies of aplite, pegmatite, liparite, etc., from intermediate and even subsilicic magmas.

Chapter XVII, treating of the diorite clan, outlines the facts showing a double mode of origin. Most pyroxene andesites are concluded to be direct differentiates of the primary basalt. Many diorites appear to represent syntectic or mixed magmas, such as those normally expected by the solution of rock from the acid earth-shell with the primary basalt. Mica andesite and hornblende andesite find their theoretical place as either syntectics or, more commonly, differentiates of syntectics.

Chapter XVIII contains an abridged statement of the relation of the eclectic theory to the granodiorites and their allies (tonalites, many quartz diorites, many dacites, etc.). They have the same origin as that of most granites, but differ from the latter rocks chemically because of the large amounts of argillaceous sediments and associated mediosilicic rocks which, together with the acid earth-shell, have been assimilated in granodioritic batholiths.

Chapter XIX indicates the great variety of species included with the syenites proper and their allies. It is recalled that these types never form the principal rocks in very large bodies, implying that their parent magmatic wedges were small. A table, found in Appendix C, illustrates the rule that members of the syenite clan are very generally eruptive into mediosilicic or subsilicic sediments. On account of the specially great fluxing power of such sediments, their assimilation near the top of a narrow abyssal wedge must tend to counteract the acidification due to solution of the acid earth-shell beneath. The final differentiate of the whole mixture should, therefore, be less silicious than that normally expected in a greater wedge, which, on account of its larger supply of heat (less sudden chilling at contacts, etc.), dissolves relatively more of the thick acid shell. Syenite is thus interpreted as a desilicated granite. The field and chemical relations of the syenites are found to correspond to the theory. The influence of the volatile matter absorbed with or from the sediments is emphasized. A few sills, showing syenite as a small-scale differentiate of basaltic magma invading basic sediments, are regarded as excellent corroborations of the general theory.

In Chapter XX nearly one-third of the recognized igneous-rock species are considered together, under the name "alkaline clans." These include most of the so-called "alkaline" rocks. They are explained by the same principles as those used for the granodiorite and syenite clans. As a rule, the alkaline rocks are differentiates from mixed magmas which are controlled in their composition and in their splitting by absorbed carbonate sediments. Because of its infinitely low content of silica, limestone or dolomite must tend to desilicate markedly the total solution in an abyssal basaltic wedge. Herein is the preferred explanation of the characteristic crystallization of minerals like leucite, nephelite, sodalite, etc., in alkaline rocks. Yet more signally than with the syenites, the highly alkaline rocks show the expected influence of gaseous transfer in segregating submagmas. Carbonate control in the formation of most alkaline rocks is strongly suggested by the table of their field relations, given in Appendix D; by the mineralogy and chemistry of the rocks; and by the relatively small volume assignable to every recorded body of this kind. A multitude of facts substantiate the thesis that the carbonate syntectics have been formed in magmas which were originally of basaltic composition. However, as expected by the theory, some alkaline rocks are manifestly due to segregation of sedimentary origin by water-gas and it is probable that the "juvenile" or primary gases of the substratum material have similarly functioned in the development of some alkaline-rock bodies.

Chapter XXI contains a short sketch of the peridotite clan (including the pyroxenites and hornblendites) and the magmatic ores. The eclectic theory explains their very common field relations to members of the gabbro clan; the rocks are interpreted as, in part, direct differentiates of basaltic magma; in other part, they are differentiates of syntectics. The splitting is often clearly gravitative. In many cases, however, the segregation has been more or less evidently due to gaseous transfer from intrusive magmas, especially those affected by the solution of sediments.

The last chapter sketches the result of matching the eclectic theory with the geology of the North American Cordillera and thus with a very extensive *assemblage* of igneous clans. This region offers all the important problems in petrogenesis.

PART I

CHAPTER II

CLASSIFICATION OF IGNEOUS ROCKS

The greater part of the earth's visible rock-matter is crystalline; only a minute percentage is composed of glass. The nature and relative proportions of the constituent crystals or minerals determine the essential nature of each holocrystalline rock. Actual mineralogical composition is a natural basis for a classification of the rocks and it must always remain the working basis for field classification. Yet there are two chief difficulties standing in the way of a perfect application of this principle. No direct method has ever been devised for the accurate measurement of the proportions of minerals in fine-grained rocks, nor is it likely that such a method is at all possible. Secondly, even if such a measuring device were in hand, the results of its use must be imperfect, since, with few exceptions, each mineral species in rocks is itself of variable composition. The principal minerals generally occur in "mixed crystals." Each of these is composed of mixtures of two or more different molecules, and the proportions in each mixture form an infinite series within the chemical limits set by the pure molecules. Examples are now familiar in the highly important feldspar, pyroxene, amphibole, and mica families. Quartz is the only principal constituent of igneous rocks which always shows the same composition.

These facts have long been recognized by petrographers and the basis for an ultimate classification is now universally found in the chemical analysis (total analysis) of the rocks.

Mode and Norm Classifications

The leading petrographers of Europe have not been disheartened by the general failure to read out the exact nature of an igneous rock, that is, its chemical composition, from its mineralogical composition. They have shown abundantly that there is usually a certain degree of correspondence between the mineralogical composition of a rock and its total analysis, so that, in most cases, a general idea of the one can be obtained if the other is known. The world leader, Rosenbusch, has prepared an elaborate classification founded on mineralogical composition, which has been largely kept under the control of chemical analysis. This system may be called the "Mode" classification, since it is based on the actual mode in which the constituent minerals are aggregated in the rock fabrics.

On the other hand, certain American petrographers have cut the Gordian knot by ignoring the "mode" in their primary classification. Instead of the actual minerals, "standard" minerals or molecules are calculated from the total analyses, and the rocks are classified according to the nature of the "norm" or whole group of standard minerals calculated for each rock.[1] This system may be called the "Norm" classification.

The reader must be referred to other works for discussion as to the relative merits of these two systems.[2] One or two remarks only will here be offered to suggest the full reason why the Mode classification will be used in this book.

In the first place, the Norm system, as announced and practised by its authors and by a considerable number of followers, is largely founded not on proved facts, but on assumptions concerning chemical "affinities," and the march of molecular formation in natural magmas. The substructure of the system is thus insecure; yet very slight changes in this substructure must entail drastic changes in the present classification itself or ruin it entirely. In a word, the Norm system is almost sure to be found too sensitive to the discovery of new *facts* concerning molecular development in silicate melts. We may be reasonably sure that present opinion regarding this fundamental matter is bound to be more or less changed in the near future. The danger is great that the ingenious but much too delicate Norm classification, together with a great mass of time-consuming labor in calculations and descriptions, will turn out to have little permanent value as a system, however valuable its invention has been in stimulating petrographic thought along chemical lines.

Again, this system is defective, as even its minor subdivisions individually include rock types which are strongly contrasted chemically and separate others which are almost alike chemically, mineralogically, and genetically. Examples may be taken almost at random. On the same page of Washington's tables (p. 164 of Prof. Paper 14, U. S.

[1] *Quantitative Classification of Igneous Rocks*, by W. Cross, J. P. Iddings, L. V. Pirsson, and H. S. Washington, Chicago, 1903. See especially page 147 for definitions of "mode" and "norm."

[2] A. Harker, *The Natural History of Igneous Rocks*, New York, 1909, p. 362, and Geol. Mag., Vol. 10, 1903, p. 173; F. W. Clarke, Bull. 491, U. S. Geol. Survey, 1911, p. 403; W. Cross, Quart. Jour. Geol. Soc., Vol. 66, 1910, p. 470; H. S. Washington, Prof. Paper 14, U. S. Geol. Survey, 1903, p. 49; J. P. Iddings, *Igneous Rocks*, Vol. 1, New York, 1909, p. 407.

Geol. Survey, 1903), which are based on the Norm classification, we find that the subrang, "toscanose," includes types containing principal oxides as follows:

	Aplite	Trachyte
SiO_2	76.03	62.33
Al_2O_3	13.39	17.30
Na_2O	2.98	4.21
K_2O	5.18	4.46

On page 320 of the same work, the subrang, "camptonose," includes a typical camptonite with 43.98 per cent. of silica and a quartz basalt with 54.56 per cent. of silica.

In the Rosita Hills district of Colorado two syngenetic rhyolites give these analyses:

	Round Mountain	Silver Cliff
SiO_2	75.20	75.39
Al_2O_3	12.96	13.65
Fe_2O_3	.37	.38
FeO	.27	.18
MnO	.03	.14
MgO	.12	.15
CaO	.29	.51
Na_2O	2.02	1.84
K_2O	8.38	6.81
H_2O	.58	1.13
	100.22	100.18

The Round Mountain rhyolite appears in the Norm classification as a member of the subrang, omeose, of the rang, liparase, in the persalane order, brittanare. The Silver Cliff rhyolite falls in the subrang, magdeburgose, of the rang, alaskase, in the persalane order, columbare.[1]

These few illustrations suffice to show that this system disregards vital principles of scientific classification. From the standpoint of the geologist it is like a zoological system which would place in the same species the Newfoundland cod, the North Sea herring, and the Louisiana alligator, while specifically separating the New England cod from the Labrador cod of slightly different size. As one of the authors of the Norm classification remarks, "the norm is primarily a means of comparison, and has in itself nothing to do with system."[2]

The field geologist has little choice as to his method of rock classification. He must judge a rock by its actual mineral constitution. The scale of his operations is usually much too great that he can hope to secure, from government laboratories or otherwise, the

[1] H. S. Washington, op. cit., pp. 125 and 143.

[2] W. Cross, Quart. Jour. Geol. Soc., Vol. 66, 1910, p. 496.

number of chemical analyses requisite to map his igneous rocks by the Norm system. If he did possess unlimited access to the resources of chemical laboratories, his norms calculated for the different phases of the average large body of igneous rock would be found to correspond to many species in the present Norm classification. Actual experience has already shown that so many species appear in such a body that their mapping is impracticable. Further, the present system contains no compelling principle to guide the field geologist in combining the "species" of this classification into larger units suitable for the practical geological mapping of the world. In any case, the Norm classification as now developed is not workable in the practical mapping of the larger rock bodies encountered in regular government surveys. On the other hand, the Mode classification has borne this test, on the whole, very well, so that many essential facts concerning the igneous rocks of the world are already amply recorded in existing maps and memoirs.

This is, in reality, the obvious ground for preferring the Mode classification as a basis for the present discussion of igneous rocks. Through it the facts of nature have been recorded and only in that record can the material be found for a synthetic study.

Rosenbusch System.—The Mode classification has been issued, so to speak, in several editions. Zirkel, Rosenbusch, Michel Lévy, Loewinson-Lessing, and others have constructed as many systems, differing in detail but all founded on mineralogical composition supplemented by chemical analysis. The latest and most comprehensive system, that of Rosenbusch, has been the edition most extensively used by geologists and they have used it with fair consistency. It will be employed in the following chapters both in the quotation of facts and in the discussion of those facts. For a description of Rosenbusch's system itself the reader is referred to his two masterly works, the "Mikroskopische Physiographie der Massigen Gesteine," vierte Auflage, Stuttgart, 1907–08, and the "Elemente der Gesteinslehre," dritte Auflage, Stuttgart, 1910. In many essential respects the systems described in Zirkel's great Lehrbuch der Petrographie, in Teall's classic work on British Petrography, and in Iddings's more recent book on Igneous Rocks are similar to that of Rosenbusch.

As Rosenbusch himself, with successive editions of his hand-book, developed and changed his classification, so we must expect the new knowledge of the future to modify the system. To become an ideal Mode classification it should be made quantitative. For the plutonic species (genetically by far the most important) Rosiwal's method of optical measurement has made an approach to this ideal already possible; and the writer believes that Rosenbusch's present classification of the plutonic rocks could be made quantitative without an intolerable amount of changes in his definitions.

Adopted Mode Classification.—However, we are here not primarily concerned with the present merits or future prospects of this system. The important point is that it is the vehicle which bears most of the facts now known about the character and distribution of terrestrial rocks. As a convenient guide Table I, based on F. E. Wright's statement of Rosenbusch's classification, has been prepared. At some points the table differs from that which would summarize his hand-book with perfect fidelity. For example, the granodiorites are here recognized as forming a distinct family. This has been done partly in order to emphasize the enormous importance of the granodiorites and their allies in the two Americas. A thorough-going division into an alkaline series and a subalkaline (lime-alkali) series is not made, for two reasons; first, to save space, and secondly, to emphasize the writer's belief that there is no petrogenic reason for making so formal, clean-cut separation. (See Chapter XX.) In spite of such subjective elements in the table, it is offered as a mnemonic aid in appreciating the actual diversity of igneous rocks.

Average Composition of Igneous-rock Species

On the chemical side the classification is illustrated by Table II. Its nature is explained in a few paragraphs here quoted from a publication issued by the writer in 1910.[1]

Since compiling the averages stated in the 1910 paper, the writer has been able to improve certain of them. In most cases the number of analyses averaged for each of these species has been increased, and often a better selection has been possible through the use of additional material. In both respects the recent (third) edition of Rosenbusch's "Elemente der Gesteinslehre" gave exceptional aid in the preparation of the new averages. The list of types for which the averages have been improved includes rhomb-porphyry, lherzolite, pyroxenite, wehrlite, harzburgite, dunite, all peridotites, picrite, essexite, trachydolerite, limburgite, ijolite, Hawaiian basalt, and melilite basalt. Averages for nineteen types, not entered in the 1910 table, have been

[1] R. A. Daly, Proceedings of the American Academy of Arts and Sciences, Vol. 45, 1910, pp. 211–240.

TABLE I.—MODE CLASSIFICATION OF THE IGNEOUS ROCKS

Controlling Components		Plutonic Rocks	Effusive Rocks	Aschistic Dike-rocks
Alkali-feldspar + quartz.		*Granite Family.* Alkaline { Biotite granite. Amphibole granite. Pyroxene granite.	*Rhyolite Family.* Alkaline { Comendite and quartz keratophyre.	*Granite Porphyry Family.* Alkaline granite porphyry. (Several types).
	With essential acid plagioclase, subordinate to orthoclase.	Subalkaline { Biotite granite. Muscovite-biotite granite. Amphibole granite. Pyroxene granite.	Subalkaline { Rhyolite, liparite, and quartz porphyry.	Granite porphyry. (Several types).
Alkali-feldspar		*Syenite Family.* Alkaline { Mica syenite. Nordmarkite. Pulaskite. Hedrumite. Amphibole syenite. Umptekite. Pyroxene syenite. Aegerite syenite. Laurvikite. Akerite.	*Trachyte Family.* Alkaline { Alkaline trachyte, pantellerite, keratophyre, and rhomb-porphyry.	*Syenite Porphyry Family.* Alkaline syenite porphyry. (Several types).
	With essential plagioclase.	Monzonite. "Quartz monzonite" (in part).	Latite.	Monzonite porphyry.
		Subalkaline { Mica syenite. Hornblende syenite. Pyroxene syenite.	Subalkaline { Mica trachyte. Pyroxene trachyte.	Subalkaline syenite porphyry.
Alkali-feldspar + nephelite or leucite.		*Nephelite Syenite Family.* Foyaite. Laurdalite. Sodalite syenite. Cancrinite syenite. Leucite syenite.	*Phonolite Family.* Phonolite, leucite phonolite, and leucitophyre.	*Nephelite Porphyry-Leucite Porphyry Family.*
		Shonkinite Family. Shonkinite. Malignite.	(*Leucite tephrite-Leucite basanite Family.*) (Here chemical, not mineralogical correspondence to the plutonic type.)	*Shonkinite Porphyry Family.*
Acid to medium plagioclase + quartz + subordinate alkali-feldspar.		*Granodiorite Family.* Granodiorite. Tonalite. "Quartz monzonite" (in part). Quartz diorite (in part).	*Dacite Family.* Mica dacite. Amphibole dacite. Pyroxene dacite.	*Granodiorite Porphyry Family.* (Several types).
Acid to medium plagioclase,		*Diorite Family.* Quartz diorite (in part). Mica diorite. Hornblende diorite. Pyroxene diorite.	*Andesite Family.* Mica andesite. Hornblende andesite. Augite andesite. Hypersthene andesite.	*Diorite Porphyrite Family.* Quartz diorite porphyrite (in part). Mica diorite porphyrite, hornblende diorite porphyrite, and augite diorite porphyrite.
Basic plagioclase + subordinate alkali-feldspar.		*Essexite Family.*	*Trachydolerite Family.*	

Basic plagioclase.	*Gabbro Family.* Gabbro. Olivine gabbro. Norite. Olivine norite. Amphibole gabbro. Troctolite. Anorthosite. Quartz gabbro.	*Basalt Family.* Basalt, melaphyre, and diabase. Quartz basalt.	*Gabbro Porphyrite Family.*
Basic plagioclase + nephelite.	*Theralite Family.*	*Nephelite tephrite-Nephelite basanite Family.*	
Nephelite.	*Ijolite-Bekinkinite Family.* Ijolite. Bekinkinite.	*Nephelite basalt-Nephelinite Family.*	
	Urtite.		
Leucite.	*Missourite-Fergusite Family.* Missourite. Fergusite.	*Leucite basalt-Leucitite Family.*	
Melilite.		*Melilite basalt Family.* Melilite basalt. Melilite-nephelite basalt.	
Olivine.	*Peridotite Family.* Mica peridotite. Amphibole peridotite. Wehrlite. Harzburgite. Lherzolite. Dunite.	*Picrite Family.* Picrite. Picrite porphyrite.	
Pyroxene (I).	*Pyroxenite Family.* Websterite. Bronzitite. Hypersthenite. Diallagite.		
Pyroxene (II).		*Limburgite and Augitite.*	
Amphibole.	*Hornblendite.*		
			Diaschistic Dike-rocks. Specially associated with subalkaline magmas: Aplite, pegmatite, malchite, beerbachite, minette, kersantite, vogesite, odinite. Specially associated with alkaline magmas: Alkali aplite, alkali pegmatite, bostonite, grorudite, sölvsbergite, tinguaite, camptonite, monchiquite, alnöite.

inserted in Table II. These are: alkaline granite, subalkaline granite, comendite, subalkaline syenite, subalkaline hornblende syenite, subalkaline mica syenite, subalkaline augite syenite, umptekite, alkaline trachyte, subalkaline trachyte, pantellerite, tonalite, quartz monzonite, mica peridotite, amphibole peridotite, "pyroxenite of the alkaline series," "pyroxenite of the subalkaline series," bekinkinite, and melilite-nephelite basalt.

Rosenbusch and his followers recognize some latitude of variation in the composition of each rock-type. The variation is both mineralogical and chemical, two rock specimens referred to a type showing differences in the proportions of the chemical elements found by analysis of the two rocks. In fact, no two analyses of granite, andesite, or any other one type have ever given precisely the same proportions of the dozen or more oxides which regularly make up an igneous rock. It is obvious that the student of map and memoir should, for many problems, have at hand the actual figures showing the most typical chemical composition of the rock-types to which his study is directed. In numerous cases an analysis of a single specimen is not so useful as that which could be made from a thorough mixture of specimens of the same rock-variety from all places on the globe where that variety occurs.

For obvious reasons such ideal analyses have never been made. In their stead the writer believes that the investigator of petrogenic and other world problems may well use the averages calculated from the many excellent chemical analyses of rocks made since Rosenbusch's system of naming and classification has been in general use. It may, indeed, be argued that such averages would more nearly represent the chemistry of Rosenbusch's types than the corresponding individual analyses which he has published in his treatise. These averages would be chemical "center-points" in his system of classification as *actually applied* to the terranes of the world.

So far as the writer is aware, the preparation of these averages has not hitherto been attempted to such an extent as to cover the chief families and species of igneous rocks. An approximation to the desired results is offered in the following table.

The work of computing the averages has been lessened very greatly by the publication of Osann's "Beiträge zur chemischen Petrographie" (2nd part, Stuttgart, 1905). This remarkable book contains, in convenient arrangement, the statement of most of the eruptive-rock analyses (over 2400 in number) published in the interval between 1883 and 1901. The period of seventeen years lies within that during which systematic petrography has been dominated by Rosenbusch's names and definitions. In general, the number of analyses for each rock-species is so large that their average would be but slightly modified by the inclusion of the analyses made since 1900. In many cases, therefore, the extended labor required to search out from the literature the additional analyses has not been considered necessary for the preparation of useful averages. For other averages it was necessary to include analyses published since 1900. The sources of such information are indicated below. Fortunately for the purpose, nearly the entire period since 1884 has seen the application of more or less refined methods of analysis; so that errors of observation for the leading oxides are relatively small.

The method of computation used is essentially like that employed by Washington and Clarke in their respective calculation of the "average composition" of all igneous rocks. In general, only the twelve more important oxides (including MnO) are recognized in the following tables. Distinctly "inferior" analyses were not considered. In each case the average was computed according to the actual numbers of determinations made by the analysts. Table XX, appendix A, shows these numbers for the respective rock-types, each column being headed by a key-number which corresponds with the named types of Table II. For some of the rocks BaO and SrO were computed. Their sum appears in the averages for CaO, as indicated in the tables. Similarly, CO_2 and Cr_2O_3 were sometimes averaged and entered with H_2O and Fe_2O_3 respectively. As expected from the method employed, the average totals nearly always ran well over 100 per cent. All averages were reduced to 100 per cent. and entered in Table II. Each average analysis was then recalculated to 100 per cent. after H_2O (and CO_2) had been subtracted. The results are also given in Table II, in which plutonics and corresponding effusives are grouped together. Magmatic relationships are often less obscured if these volatile oxides, which may be wholly or in part of exotic nature, are excluded. Finally, in order to facilitate reference to the tables, an index to the different rock-types was prepared and may be found below Table II.

It will be observed that certain rock-types have been omitted from the tables. The large class of "aschistic" dike-rocks is not represented because of their chemical similarity to the corresponding plutonic species. Other named varieties are omitted since their analyses are too few to give useful averages. In a few cases the mineralogical and chemical variations within each variety are so great that it has not seemed advisable to regard their averages as worthy of entry. Many other subordinate varieties of rock, though given special names, are chemically almost identical with the more important types entered in the tables and therefore have been excluded.[1]

[1] The immediate sources of the analytical statements used in the computations are as follows:

1. Beiträge zur chemischen Petrographie, zweiter Teil, by A. Osann. Stuttgart, 1905.
2. Chemical Analyses of Igneous Rocks published from 1884 to 1900, by H. S. Washington. Prof. Paper, No. 14, U. S. Geological Survey, 1903.
3. Elemente der Gesteinslehre, 2nd and 3rd editions, by H. Rosenbusch. Stuttgart, 1901 and 1910.
4. Studien über die Granite von Schweden, by P. J. Holmquist. Bull. Geol. Institution, University of Upsala, Vol. 7, 1906, p. 76.
5. Some Lava Flows of the Western Slope of the Sierra Nevada, California, by F. L. Ransome. Amer. Jour. Science, Vol. 5, 1898, p. 355.
6. A. Lacroix, Matériaux pour la Minéralogie de Madagascar. Nouv. Archives du Muséum, (4), Vol. 5, Paris, 1903.
7. Geology of the Yellowstone National Park, by A. Hague and others. Petrography by J. P. Iddings. Monograph No. 32, Part 2, U. S. Geological Survey, 1899.
8. Analyses of Rocks from the Laboratory of the United States Geological Survey, 1880 to 1908, by F. W. Clarke. Bulletin 419 of the Survey, 1910.
9. Geological and Petrographical Studies of the Sudbury Nickel District, by T. L. Walker, Quart. Jour. Geol. Soc., Vol. 53, 1897, p. 40.
10. Petrography and Geology of the Igneous Rocks of the Highwood Mountains, Montana, by L. V. Pirsson. Bull. 237, U. S. Geological Survey, 1905.
11. Geology of the North American Cordillera at the Forty-ninth Parallel, by R. A. Daly (Memoir No. 38, Geol. Survey of Canada, 1912, pp. 793–799).

The sources of the analyses used in each average are indicated by the authors' names at the head of the corresponding columns in Table II. In the future all the averages can be improved by considering also the thousands of analyses published since 1900 and not here employed. Such new averages can be advantageously made if the data of Tables II and XX are combined.

TABLE II.—SHOWING THE AVERAGE COMPOSITIONS CALCULATED FOR THE PRINCIPAL IGNEOUS-ROCK TYPES

GROUP I

	Plutonic				Effusive			
	1	2	3	4	5	6	7	8
	Pre-Cambrian granites including 16 analyses of Swedish types (Osann)	Pre-Cambrian granites of Sweden (Holmquist)	Granites younger than the pre-Cambrian (Osann and Clarke)	Granite of all periods (Osann and Clarke)	Liparite, including 40 rhyolites (Osann)	Liparites, as named by authors (Osann)	Rhyolites, as named by authors (Osann)	Quartz porphyry (Osann)
No. of analyses	47	114	184	236	64	24	40	50
SiO_2	71.06	69.81	69.73	69.92	72.60	72.90	72.62	72.36
TiO_2	.48	.54	.34	.39	.30	.48	.25	.33
Al_2O_3	14.10	13.76	14.98	14.78	13.88	14.18	13.77	14.17
Fe_2O_3	1.46	2.17	1.62	1.62	1.43	1.65	1.29	1.55
FeO	1.63	1.87	1.66	1.67	.82	.31	.90	1.01
MnO	.18	.26	.11	.13	.12	.13	.12	.09
MgO	.59	.84	1.08	.97	.38	.40	.38	.52
CaO	1.97[1]	2.20	2.20[2]	2.15[3]	1.32	1.13	1.43	1.38
Na_2O	3.24	3.17	3.28	3.28	3.54	3.54	3.55	2.85
K_2O	4.50	4.38	3.95	4.07	4.03	3.94	4.09	4.56
H_2O	.69	.74	.78	.78	1.52	1.33	1.53	1.09
P_2O_5	.10	.26	.27	.24	.06	.01	.07	.09
Calculated as Water-free								
SiO_2	71.56	70.33	70.28	70.47	73.72	73.89	73.75	73.16
TiO_2	.48	.54	.34	.39	.30	.49	.25	.33
Al_2O_3	14.20	13.86	15.10	14.90	14.10	14.37	13.99	14.33
Fe_2O_3	1.47	2.19	1.63	1.63	1.45	1.67	1.31	1.57
FeO	1.65	1.89	1.67	1.68	.83	.31	.91	1.02
MnO	.18	.26	.11	.13	.12	.13	.12	.09
MgO	.59	.85	1.09	.98	.40	.41	.39	.53
CaO	1.98[1]	2.22	2.22[2]	2.17[3]	1.34	1.14	1.45	1.39
Na_2O	3.26	3.19	3.31	3.31	3.59	3.59	3.60	2.88
K_2O	4.53	4.41	3.98	4.10	4.09	3.99	4.16	4.61
P_2O_5	.10	.26	.27	.24	.06	.01	.07	.09
Each sum = 100.00								

[1] Includes .08 per cent. BaO and .01 per cent. SrO.

[2] Includes .06 per cent. BaO and .02 per cent. SrO.

[3] Includes .06 per cent. BaO and .02 per cent. SrO.

GROUP II

	Plutonic		Effusive	
	9	10	11	12
	Subalkaline granite (Rosenbusch)	Alkaline granite (Rosenbusch)	Comendite (Rosenbusch)	Quartz keratophyre (Rosenbusch)
No. of analyses	20	12	6	13
SiO_2	69.21	73.30	74.44	75.45
TiO_2	.41	.11	.19	.17
Al_2O_3	14.41	12.33	11.27	13.11
Fe_2O_3	1.98	2.58	2.78	1.14
FeO	1.67	1.28	.94	.66
MnO	.12	.02	.08	.29
MgO	1.15	.26	.35	.34
CaO	2.19	.46	.21	.83
Na_2O	3.48	4.55	4.18	5.88
K_2O	4.23	4.20	4.95	1.26
H_2O	.85	.86	.59	.69
P_2O_5	.30	.05	.02	.18
Calculated as Water-free				
SiO_2	69.82	73.94	74.88	75.98
TiO_2	.41	.11	.19	.17
Al_2O_3	14.53	12.44	11.34	13.20
Fe_2O_3	2.00	2.60	2.80	1.15
FeO	1.68	1.29	.95	.66
MnO	.12	.02	.08	.29
MgO	1.16	.26	.35	.34
CaO	2.21	.46	.21	.84
Na_2O	3.51	4.59	4.20	5.92
K_2O	4.26	4.24	4.98	1.27
P_2O_5	.30	.05	.02	.18

Each sum = 100.00

GROUP III

	Plutonic					Effusive	
	13	14	15	16	17	18	19
	Subalkaline hornblende syenite (Rosenbusch, Clarke)	Subalkaline mica syenite (Rosenbusch)	Subalkaline augite syenite (Rosenbusch, Clarke)	Subalkaline syenite, all types (Rosenbusch, Clarke)	All syenite, including five analyses of alkaline types	Trachyte (Osann, Rosenbusch)	Subalkaline trachyte (Rosenbusch)
No. of analyses	7	2	2	11	50	48	10
SiO_2	60.79	59.25	51.59	58.65	60.19	60.68	63.91
TiO_2	.80	.79	.61	.86	.67	.38	.59
Al_2O_3	16.10	15.28	18.77	16.38	16.28	17.74	15.88
Fe_2O_3	3.21	2.59	6.11	3.65	2.74	2.64	3.22
FeO	2.92	3.47	3.26	3.09	3.28	2.62	2.23
MnO	.11	....	.24	.15	.14	.06	.01
MgO	2.20	5.07	4.11	3.06	2.49	1.12	1.14
CaO	3.87	3.68	7.35	4.45	4.30	3.09	2.81
Na_2O	3.37	3.10	4.35	3.48	3.98	4.43	3.08
K_2O	5.43	4.41	2.99	4.79	4.49	5.74	5.80
H_2O	.90	2.06	.26	1.13	1.16	1.26	1.28
P_2O_5	.30	.30	.36	.31	.28	.24	.05
Calculated as Water-free							
SiO_2	61.34	60.49	51.72	59.32	60.90	61.46	64.74
TiO_2	.81	.80	.61	.87	.68	.38	.60
Al_2O_3	16.25	15.60	18.82	16.56	16.47	17.97	16.09
Fe_2O_3	3.24	2.65	6.13	3.69	2.77	2.67	3.26
FeO	2.95	3.55	3.27	3.13	3.32	2.66	2.26
MnO	.11	....	.24	.15	.14	.06	.01
MgO	2.22	5.17	4.12	3.10	2.52	1.13	1.15
CaO	3.90	3.76	7.37	4.50	4.35	3.13	2.85
Na_2O	3.40	3.17	4.36	3.52	4.03	4.49	3.12
K_2O	5.48	4.50	3.00	4.85	4.54	5.81	5.87
P_2O_5	.30	.31	.36	.31	.28	.24	.05
Each sum = 100.00							

GROUP IV

	Plutonic					Effusive		
	20	21	22	23	24	25	26	27
	Nordmarkite (Osann, Washington)	Pulaskite (Osann, Washington)	Akerite (Osann, Washington)	Umptekite (Rosenbusch)	Average alkaline syenite, including 7 nordmarkitis, 5 pulaskites, 9 akerites, and 3 laurvikites.	Alkaline trachyte (Rosenbusch)	Keratophyre (Osann, Washington)	Pantellerite (Rosenbusch)
No. of analyses	7	5	8	5	23	19	7	12
SiO_2	64.36	61.86	61.96	60.01	61.99	62.63	61.51	68.63
TiO_2	.45	.15	.99	.64	.56	.62	.45	.35
Al_2O_3	16.81	19.07	17.07	16.65	17.93	17.06	17.37	10.30
Fe_2O_3	1.08	2.65	2.35	2.41	2.22	3.01	1.92	5.60
FeO	2.71	1.49	3.37	3.85	2.29	1.98	3.35	2.61
MnO	.15	.01	.09	.18	.08	.13	.01	.21
MgO	.72	.55	1.38	.97	.96	.63	1.26	.37
CaO	1.55	1.47	3.41	2.62	2.55	1.51	1.08	1.07
Na_2O	5.76	6.45	4.65	6.53	5.54	6.26	5.23	6.14
K_2O	5.62	5.75	3.80	5.47	4.98	5.37	5.29	4.17
H_2O	.70	.47	.93	.50	.76	.71	2.45	.53
P_2O_5	.09	.08	....	.17	.14	.09	.08	.02
	Calculated as Water-free							
SiO_2	64.81	62.15	62.55	60.32	62.46	63.09	63.06	69.00
TiO_2	.45	.15	1.00	.64	.56	.62	.46	.35
Al_2O_3	16.93	19.16	17.23	16.74	18.07	17.18	17.81	10.36
Fe_2O_3	1.09	2.66	2.37	2.42	2.24	3.03	1.97	5.63
FeO	2.73	1.50	3.40	3.87	2.31	2.00	3.43	2.62
MnO	.15	.01	.09	.18	.08	.13	.01	.21
MgO	.73	.55	1.39	.97	.97	.63	1.29	.37
CaO	1.56	1.48	3.44	2.63	2.57	1.52	1.11	1.08
Na_2O	5.80	6.48	4.69	6.56	5.58	6.30	5.36	6.17
K_2O	5.66	5.78	3.84	5.50	5.02	5.41	5.42	4.19
P_2O_5	.09	.08	....	.17	.14	.09	.08	.02
	Each sum = 100.00							

GROUP V

	Plutonic	Effusive	Plutonic	Effusive
	28	**29**	**30**	**31**
	Laurvikite (Osann)	Rhomb-porphyry (Washington)	Monzonite (Osann and (Washington)	Latite (Ransome and Daly)
No. of analyses	3	7	12	10
SiO_2	57.45	56.36	55.25	57.65
TiO_2	....	.48	.60	1.00
Al_2O_3	21.11	20.10	16.53	16.68
Fe_2O_3	2.89	2.86	3.03	2.29
FeO	2.39	2.01	4.37	4.07
MnO	....	.01	.15	.10
MgO	1.06	1.15	4.20	3.22
CaO	4.10	2.73	7.19	5.74[1]
Na_2O	5.89	7.65	3.48	3.59
K_2O	3.87	4.97	4.11	4.39
H_2O	.70	1.20	.66	.91[2]
P_2O_5	.54	.48	.43	.36
		Calculated as Water-free		
SiO_2	57.85	57.06	55.62	58.18
TiO_2	....	.48	.60	1.01
Al_2O_3	21.26	20.35	16.64	16.84
Fe_2O_3	2.91	2.90	3.05	2.31
FeO	2.41	2.04	4.40	4.11
MnO	....	.01	.15	.10
MgO	1.07	1.16	4.23	3.25
CaO	4.13	2.76	7.24	5.79[1]
Na_2O	5.93	7.74	3.50	3.62
K_2O	3.90	5.01	4.14	4.43
P_2O_5	.54	.49	.43	.36
		Each sum = 100.00		

[1] Includes .16 per cent. BaO and .07 per cent. SrO.
[2] Includes .14 per cent. CO_2.

GROUP VI

	Plutonic				Effusive		
	32	33	34	35	36	37	38
	Foyaite (Osann and Rosenbusch)	Urtite (Osann)	Laurdalite (Osann)	Nephelite syenite (Osann)	Phonolite (Osann, Clarke, and Lacroix)	Leucite phonolite (Osann and Washington)	Leucitophyre (Washington and Rosenbusch)
No. of analyses	10	3	3	43	25	4	8
SiO_2	56.11	45.61	54.36	54.63	57.45	54.89	49.83
TiO_2	.45	....	1.30	.86	.41	....	.71
Al_2O_3	21.33	27.76	19.99	19.89	20.60	21.28	19.00
Fe_2O_3	1.87	3.67	2.79	3.37	2.35	3.04	3.17
FeO	1.47	.50	2.58	2.20	1.03	1.49	3.59
MnO	.05	.15	.18	.35	.13	.01	.17
MgO	.55	.19	1.72	.87	.30	.66	1.79
CaO	1.72	1.73	2.96	2.51	1.50	2.31	5.69
Na_2O	8.48	16.25	8.28	8.26	8.84	5.62	7.19
K_2O	6.46	3.72	4.98	5.46	5.23	8.39	6.15
H_2O	1.50	.42	.22	1.35	2.04	2.31	1.93
P_2O_5	.01	....	.64	.25	.12	....	.78
Calculated as Water-free							
SiO_2	56.96	45.80	54.48	55.38	58.65	56.19	50.82
TiO_2	.46	....	1.30	.87	.42	....	.72
Al_2O_3	21.65	27.88	20.03	20.16	21.03	21.78	19.38
Fe_2O_3	1.90	3.68	2.80	3.42	2.40	3.11	3.23
FeO	1.49	.50	2.59	2.23	1.05	1.53	3.66
MnO	.05	.15	.18	.35	.13	.01	.17
MgO	.56	.19	1.72	.88	.31	.68	1.83
CaO	1.75	1.74	2.97	2.54	1.53	2.36	5.80
Na_2O	8.61	16.32	8.30	8.38	9.02	5.75	7.33
K_2O	6.56	3.74	4.99	5.54	5.34	8.59	6.27
P_2O_5	.01	....	.64	.25	.12	....	.79
Each sum = 100.00							

GROUP VII

	Plutonic			Effusive
	39	**40**	**41**	**42**
	Tonalite (Osann, Rosenbusch)	Quartz monzonite (Clarke)	Granodiorite (Osann, Clarke)	Dacite (Osann, Rosenbusch)
No. of analyses	5	20	12	30
SiO_2	66.57	66.64	65.10	66.91
TiO_2	.54	.50	.54	.33
Al_2O_3	14.57	15.57	15.82	16.62
Fe_2O_3	2.36	1.91	1.64	2.44
FeO	4.12	1.94	2.66	1.33
MnO	.01	.06	.05	.04
MgO	1.72	1.41	2.17	1.22
CaO	3.27	3.50	4.66	3.27
Na_2O	3.22	3.41	3.82	4.13
K_2O	2.22	3.72	2.29	2.50
H_2O	.93	1.15	1.09	1.13
P_2O_5	.47	.19	.16	.08
Calculated as Water-free				
SiO_2	67.20	67.41	65.82	67.67
TiO_2	.54	.51	.55	.33
Al_2O_3	14.71	15.76	15.99	16.81
Fe_2O_3	2.38	1.93	1.66	2.47
FeO	4.16	1.96	2.69	1.35
MnO	.01	.06	.05	.04
MgO	1.74	1.43	2.19	1.23
CaO	3.30	3.54	4.71	3.31
Na_2O	3.25	3.45	3.86	4.18
K_2O	2.24	3.76	2.32	2.53
P_2O_5	.47	.19	.16	.08
Each sum = 100.00				

GROUP VIII

	Plutonic			Effusive				
	43	44	45	46	47	48	49	50
	Quartz diorite (Osann, Washington)	Diorite, including quartz diorite (Osann)	Diorite, excluding quartz diorite (Osann)	All andesite (Osann)	Augite andesite (Osann)	Hypersthene andesite (Osann)	Hornblende (amphibole) andesite (Osann)	Mica andesite (Osann)
No. of analyses	20	89	70	87	33	20	24	10
SiO_2	59.47	58.38	56.77	59.59	57.50	59.48	61.12	62.25
TiO_2	.64	.80	.84	.77	.79	.48	.42	1.65
Al_2O_3	16.52	16.28	16.67	17.31	17.33	17.38	17.65	16.10
Fe_2O_3	2.63	2.98	3.16	3.33	3.78	2.96	2.89	3.62
FeO	4.11	4.11	4.40	3.13	3.62	3.67	2.40	2.20
MnO	.08	.13	.13	.18	.22	.15	.15	.21
MgO	3.75	3.88	4.17	2.75	2.86	3.28	2.44	2.03
CaO	6.24	6.38	6.74	5.80	5.83	6.61	5.80	4.05
Na_2O	2.98	3.34	3.39	3.58	3.53	3.41	3.83	3.55
K_2O	1.93	2.09	2.12	2.04	2.36	1.64	1.72	2.44
H_2O	1.39	1.37	1.36	1.26	1.88	.74	1.43	1.50
P_2O_5	.26	.26	.25	.26	.30	.20	.15	.40
Calculated as Water-free								
SiO_2	60.31	59.19	57.56	60.35	58.65	59.92	62.01	63.20
TiO_2	.65	.81	.85	.78	.80	.48	.43	1.67
Al_2O_3	16.75	16.51	16.90	17.54	17.67	17.51	17.91	16.35
Fe_2O_3	2.67	3.02	3.20	3.37	3.85	2.98	2.93	3.67
FeO	4.17	4.17	4.46	3.17	3.69	3.70	2.44	2.23
MnO	.08	.13	.13	.18	.22	.15	.15	.21
MgO	3.80	3.93	4.23	2.78	2.90	3.31	2.48	2.06
CaO	6.33	6.47	6.83	5.87	5.92	6.66	5.88	4.11
Na_2O	3.02	3.39	3.44	3.63	3.60	3.44	3.88	3.61
K_2O	1.96	2.12	2.15	2.07	2.40	1.65	1.74	2.48
P_2O_5	.26	.26	.25	.26	.30	.20	.15	.41
Each sum = 100.00								

GROUP IX

	Plutonic		Effusive					
	51	52	53	54	55	56	57	58
	All norite (Osann, Walker)	All gabbro (Osann)	All basalt, including 161 basalts, 17 olivine diabases, 11 melaphyres, and 9 dolerites (Osann)	Basalt, as named by authors (including also anamesite, tachylite, etc.) (Osann)	Diabase (Osann)	Olivine diabase (Osann)	Melaphyre (Osann)	Dolerite (Osann)
No. of analyses	7	41	198	161	20	17	11	9
SiO_2	50.16	48.24	49.06	48.78	50.12	50.10	50.60	49.50
TiO_2	1.64	.97	1.36	1.39	1.41	1.25	.68	1.42
Al_2O_3	18.51	17.88	15.70	15.85	15.68	14.43	17.40	14.37
Fe_2O_3	1.88	3.16	5.38	5.37	4.55	5.06	4.57	6.55
FeO	9.29	5.95	6.37	6.34	6.73	6.31	6.29	5.84
MnO	.14	.13	.31	.29	.23	.25	.46	.17
MgO	5.97	7.51	6.17	6.03	5.85	7.32	4.89	7.75
CaO	7.90	10.99	8.95	8.91	8.80	9.53	8.09	9.96
Na_2O	2.72	2.55	3.11	3.18	2.95	2.75	3.23	2.50
K_2O	.80	.89	1.52	1.63	1.38	.73	1.76	.84
H_2O	.76	1.45	1.62	1.76	1.93	2.00	1.83	.66
P_2O_5	.23	.28	.45	.47	.37	.27	.20	.44
			Calculated as Water-free					
SiO_2	50.54	48.95	49.87	49.65	51.11	51.12	51.54	49.83
TiO_2	1.65	.98	1.38	1.41	1.44	1.27	.69	1.43
Al_2O_3	18.65	18.15	15.96	16.13	15.99	14.73	17.73	14.47
Fe_2O_3	1.90	3.21	5.47	5.47	4.64	5.16	4.66	6.59
FeO	9.36	6.04	6.47	6.45	6.86	6.44	6.41	5.88
MnO	.14	.13	.32	.30	.23	.25	.47	.17
MgO	6.02	7.62	6.27	6.14	5.96	7.47	4.99	7.80
CaO	7.96	11.15	9.09	9.07	8.97	9.73	8.24	10.02
Na_2O	2.74	2.59	3.16	3.24	3.01	2.81	3.29	2.52
K_2O	.81	.90	1.55	1.66	1.41	.74	1.78	.85
P_2O_5	.23	.28	.46	.48	.38	.28	.20	.44

Each sum = 100.00

GROUP X

	Plutonic				
	59	60	61	62	63
	Gabbro, excluding olivine gabbro (Osann)	Olivine gabbro (Osann)	Norite, excluding olivine norite (Osann, Walker)	Olivine norite (Osann)	Anorthosite (Osann, Washington)
No. of analyses	24	17	5	2	12
SiO_2	49.50	46.49	50.08	50.38	50.40
TiO_2	.84	1.17	1.44	2.04	.15
Al_2O_3	18.00	17.73	18.62	18.27	28.30
Fe_2O_3	2.80	3.66	2.35	.73	1.06
FeO	5.80	6.17	8.87	10.35	1.12
MnO	.12	.17	.11	.20	.05
MgO	6.62	8.86	6.22	5.32	1.25
CaO	10.64	11.48	7.89	7.91	12.46
Na_2O	2.82	2.16	2.53	3.18	3.67
K_2O	.98	.78	.71	1.02	.74
H_2O	1.60	1.04	1.01	.26	.75
P_2O_5	.28	.29	.17	.34	.05
Calculated as Water-free					
SiO_2	50.31	46.97	50.60	50.51	50.78
TiO_2	.85	1.18	1.45	2.05	.15
Al_2O_3	18.30	17.92	18.81	18.32	28.51
Fe_2O_3	2.85	3.70	2.37	.73	1.07
FeO	5.89	6.24	8.96	10.38	1.13
MnO	.12	.17	.11	.20	.05
MgO	6.73	8.96	6.28	5.33	1.26
CaO	10.81	11.60	7.97	7.93	12.55
Na_2O	2.86	2.18	2.56	3.19	3.70
K_2O	1.00	.79	.72	1.02	.75
P_2O_5	.28	.29	.17	.34	.05
Each sum = 100.00					

GROUP XI

	Plutonic							Effusive
	64	65	66	67	68	69	70	71
	Mica peridotite (Osann)	Amphibole peridotite (Rosenbusch, Clark, Washington, Osann)	Wehrlite (Osann)	Harzburgite (Osann, Washington, Rosenbusch)	Lherzolite (Osann, Rosenbusch)	Dunite (Washington, Rosenbusch, Daly)	All peridotite of columns 64–69	Picrite (Osann, Washington, Clarke)
No. of analyses	3	7	5	5	5	6	31	14
SiO_2	35.62	40.91	45.07	43.14	42.71	38.68	41.09	41.30
TiO_2	3.26	.65	.64	....	.12	....	1.16	.81
Al_2O_3	7.78	5.00	5.75	4.72	5.11	.94	4.80	9.43
Fe_2O_3	5.72	4.64	3.43	1.28	4.97	5.47	3.96	5.30
FeO	9.42	7.97	9.53	7.46	4.57	8.44	7.12	8.86
MnO	.16	.07	.26	.07	.06	.17	.10	.29
MgO	22.70	30.82	22.88	37.89	32.31	42.51	32.25	19.94
CaO	4.56	4.41	7.48	3.01	5.51	1.06	4.42	8.01
Na_2O	.43	.58	1.14	....	1.02	.03	.49	1.20
K_2O	3.32	.36	.57	....	.29	.04	.96	.39
H_2O	6.15	4.56	3.10	2.43[1]	3.32	2.63	3.53	4.27
P_2O_5	.88	.03	.15	....	.01	.03	.12	.20
Calculated as Water-free								
SiO_2	37.96	42.87	46.51	44.22	44.18	39.72	42.60	43.14
TiO_2	3.47	.68	.66	....	.12	....	1.20	.85
Al_2O_3	8.30	5.25	5.93	4.84	5.28	.96	4.97	9.85
Fe_2O_3	6.09	4.87	3.54	1.31	5.14	5.61	4.10	5.54
FeO	10.04	8.34	9.84	7.64	4.72	8.67	7.39	9.26
MnO	.17	.07	.27	.07	.06	.17	.10	.30
MgO	24.19	32.30	23.61	38.83	33.45	43.68	33.43	20.83
CaO	4.86	4.63	7.72	3.09	5.69	1.09	4.59	8.37
Na_2O	.45	.59	1.17	....	1.05	.03	.51	1.25
K_2O	3.53	.37	.59	....	.30	.04	.99	.40
P_2O_5	.94	.03	.16	....	.01	.03	.12	.21
Each sum = 100.00								

[1] Loss on ignition.

GROUP XII

	Plutonic				Effusive		
	72	73	74	75	76	77	78
	Websterite (Osann)	"Pyroxenite of sub-alkaline series" (Osann, Rosenbusch, Clarke)	"Pyroxenite of alkaline series" (Rosenbusch)	Essexite (Rosenbusch)	Trachydolerite (Rosenbusch)	Limburgite (Rosenbusch)	Augitite (Osann, Washington, Rosenbusch)
No. of analyses	4	10	3	20	34	14	6
SiO_2	53.65	51.29	44.30	48.64	49.20	41.25	42.25
TiO_2	.14	.58	2.31	1.86	1.68	1.59	2.52
Al_2O_3	1.66	3.52	8.93	17.96	16.65	12.03	16.26
Fe_2O_3	1.90	1.82	7.94	4.31	4.76	5.65	8.43
FeO	5.35	6.00	7.75	5.58	5.36	7.29	5.46
MnO	.17	.13	.23	.19	.55	.54	....
MgO	22.57	21.06	10.29	4.00	4.43	11.22	5.49
CaO	13.37	13.88	15.27	8.89	7.74	11.88	9.75
Na_2O	.20	.30	.74	4.30	4.54	3.40	4.45
K_2O	.07	.16	1.05	2.28	3.19	1.30	1.92
H_2O	.85	1.20	1.18	1.34	1.30	3.20	2.43
P_2O_5	.07	.06	.01	.65	.60	.65	1.04
	Calculated as Water-free						
SiO_2	54.11	51.91	44.83	49.31	49.85	42.62	43.30
TiO_2	.14	.59	2.34	1.88	1.70	1.65	2.58
Al_2O_3	1.67	3.57	9.03	18.20	16.88	12.43	16.67
Fe_2O_3	1.92	1.84	8.04	4.37	4.82	5.84	8.64
FeO	5.40	6.07	7.84	5.66	5.43	7.53	5.59
MnO	.17	.13	.23	.19	.56	.56	....
MgO	22.76	21.32	10.41	4.05	4.48	11.60	5.63
CaO	13.49	14.05	15.46	9.01	7.84	12.28	9.99
Na_2O	.20	.30	.75	4.36	4.60	3.48	4.56
K_2O	.07	.16	1.06	2.31	3.23	1.34	1.97
P_2O_5	.07	.06	.01	.66	.61	.67	1.07
	Each sum = 100.00						

GROUP XIII

	Plutonic		Effusive					
	79	80	81	82	83	84	85	86
	Theralite (Osann)	Shonkinite (Pirsson)	All tephrite	All basanite	Nephelite tephrite (Osann)	Leucite tephrite (Osann, Washington)	Nephelite basanite (Osann)	Leucite basanite (Osann, Washington)
No. of analyses	6	6	24	20	4	20	16	4
SiO_2	45.61	48.66	49.14	44.41	46.91	49.90	44.20	45.34
TiO_2	1.96	.97	1.00	1.56	1.81	.16	1.64	1.30
Al_2O_3	14.35	12.36	16.57	15.81	15.25	16.94	15.64	16.59
Fe_2O_3	6.17	3.08	3.65	4.66	7.70	3.02	4.35	5.83
FeO	4.03	5.86	6.68	5.85	4.06	7.15	6.14	4.76
MnO	.19	.13	.30	.14	1.43	.23	.19	.01
MgO	6.05	8.09	3.98	8.20	2.95	4.22	8.89	5.43
CaO	9.49	10.46[1]	9.88	10.12	9.36	10.04	9.74	11.64
Na_2O	5.12	2.71	2.57	3.81	4.25	2.24	4.03	2.93
K_2O	3.69	5.15	3.39	2.37	2.63	3.57	1.83	4.55
H_2O	2.60	1.46	2.00	2.42	2.51	1.74	2.67	1.12
P_2O_5	.74	1.07	.84	.65	1.14	.79	.68	.50
Calculated as Water-free								
SiO_2	46.83	49.38	50.15	45.51	48.12	50.79	45.41	45.86
TiO_2	1.98	.98	1.02	1.60	1.86	.16	1.68	1.31
Al_2O_3	14.73	12.55	16.90	16.20	15.65	17.24	16.07	16.78
Fe_2O_3	6.34	3.12	3.72	4.78	7.89	3.07	4.47	5.90
FeO	4.14	5.95	6.82	5.99	4.16	7.28	6.31	4.81
MnO	.19	.13	.31	.14	1.47	.23	.20	.01
MgO	6.22	8.21	4.06	8.41	3.02	4.30	9.13	5.49
CaO	9.75	10.62[2]	10.08	10.37	9.60	10.22	10.01	11.77
Na_2O	5.27	2.75	2.62	3.90	4.36	2.28	4.14	2.96
K_2O	3.79	5.23	3.46	2.43	2.70	3.63	1.88	4.60
P_2O_5	.76	1.08	.86	.67	1.17	.80	.70	.51
Each sum = 100.00								

[1] Includes .40 per cent. BaO and .09 per cent. SrO.

[2] Includes .41 per cent. BaO and .09 per cent. SrO.

GROUP XIV

	Plutonic		Effusive	
	87	88	89	90
	Fergusite (Pirsson)	Missourite (Pirsson, Daly)	Leucite basalt (Osann, Rosenbusch)	Leucitite (Osann, Rosenbusch)
No. of analyses	1	2	7	7
SiO_2	51.70	44.27	46.47	47.72
TiO_2	.23	1.37	1.33	.52
Al_2O_3	14.50	10.73	15.97	18.19
Fe_2O_3	5.07	3.63	5.97	4.74
FeO	3.58	5.87	4.27	3.90
MnO	.01	.06	.01	.06
MgO	4.55	13.05	5.87	3.45
CaO	7.40[1]	11.46[2]	10.54	7.27
Na_2O	2.93	1.07	1.69	4.51
K_2O	7.60	4.43	4.83	7.66
H_2O	2.25	3.23	2.32	1.51
P_2O_5	.18	.83	.73	.47
Calculated as Water-free				
SiO_2	52.89	45.75	47.58	48.45
TiO_2	.24	1.41	1.36	.53
Al_2O_3	14.83	11.09	16.35	18.47
Fe_2O_3	5.18	3.75	6.11	4.81
FeO	3.66	6.07	4.37	3.96
MnO	.01	.06	.01	.06
MgO	4.65	13.49	6.01	3.50
CaO	7.57[3]	11.85[4]	10.79	7.38
Na_2O	3.00	1.10	1.73	4.58
K_2O	7.79	4.57	4.94	7.78
P_2O_5	.18	.86	.75	.48
Each sum = 100.00				

[1] Includes .30 per cent. BaO and .07 per cent. SrO.
[2] Includes .48 per cent. BaO and .18 per cent. SrO.
[3] Includes .31 per cent. BaO and .07 per cent. SrO.
[4] Includes .50 per cent. and .19 per cent. SrO.

GROUP XV

	Plutonic		Effusive			
	91	92	93	94	95	96
	Ijolite (Rosenbusch)	Bekinkinite (Rosenbusch)	Nephelinite (Rosenbusch)	Nephelite basalt (Osann)	Melilite-nephelite basalt (Rosenbusch)	Melilite basalt (Rosenbusch, Osann)
No. of analyses	6	2	9	26	5	5
SiO_2	42.81	41.70	41.17	39.87	37.56	35.72
TiO_2	1.56	2.70	1.35	1.50	2.66	4.78
Al_2O_3	18.95	14.50	16.83	13.58	10.08	9.56
Fe_2O_3	3.86	5.13	7.61	6.71	6.82	5.41
FeO	4.84	7.09	6.64	6.43	5.94	6.55
MnO	.19	....	.16	.21	.06	....
MgO	3.16	9.26	3.72	10.46	15.32	15.46
CaO	10.47	12.20	10.12	12.36	13.82	14.20
Na_2O	9.63	3.59	6.45	3.85	3.11	3.35
K_2O	2.26	1.18	2.49	1.87	1.53	1.67
H_2O	.85	1.80	2.42	2.22[1]	2.52	2.67
P_2O_5	1.42	.85	1.04	.94	.58	.63
Calculated as Water-free						
SiO_2	43.18	42.47	42.19	40.77	38.54	36.70
TiO_2	1.56	2.75	1.38	1.53	2.73	4.91
Al_2O_3	19.12	14.77	17.25	13.88	10.35	9.82
Fe_2O_3	3.89	5.22	7.79	6.86	7.00	5.55
FeO	4.88	7.22	6.81	6.57	6.09	6.73
MnO	.19	....	.17	.21	.06	....
MgO	3.19	9.42	3.81	10.73	15.70	15.89
CaO	10.56	12.42	10.37	12.65	14.17	14.59
Na_2O	9.72	3.66	6.61	3.94	3.19	3.44
K_2O	2.28	1.20	2.55	1.90	1.57	1.72
P_2O_5	1.43	.87	1.07	.96	.60	.65
Each sum = 100.00						

[1] Includes 0.29 per cent. CO_2.

GROUP XVI

	Plutonic			Effusive					
	97	98	99	100	101	102	103	104	105
	Alaskite (Osann)	Diorite of Electric Peak (Rosenbusch)	Malignite (Osann, Daly)	Rhyolite of Yellowstone Park (Iddings)	Basalt of Hawaii (Osann)	Banakite (Osann)	Shoshonite (Osann)	Absarokite (Osann)	Leucite absarokite (Osann)
No. of analyses	3	10	4	10	20	4	8	5	2
SiO_2	76.47	62.21	50.34	74.04	48.90	52.04	53.56	50.11	47.45
TiO_2	.07	.60	.34	.18	1.71	.76	.82	.96	.81
Al_2O_3	13.03	16.45	14.75	13.19	13.94	17.65	17.88	13.04	11.43
Fe_2O_3	1.04	2.53	4.18	1.35	5.59	4.66	4.51	4.58	3.22
FeO		2.89	2.75	1.01	8.63	2.75	3.05	3.94	5.78
MnO	.01	.02	.11	.04	.53	.13	.07	.11	.12
MgO	.06	3.32	4.23	.32	6.39	3.33	3.62	9.27	14.60
CaO	.45	4.96	10.43	1.19	9.05	5.11	6.45	7.63	8.18
Na_2O	3.53	3.88[1]	5.27	3.88	3.22	4.10	3.41	1.94	2.32
K_2O	4.81	2.21	5.21	3.75	1.03	5.03	3.76	4.15	2.99
H_2O	.52	.80[2]	1.20	1.02[3]	.73	3.74	2.32	3.58	2.50
P_2O_5	.01	.13	1.19	.03	.28	.70	.55	.69	.60
Calculated as Water-free									
SiO_2	76.87	62.71	50.95	74.80	49.27	54.06	54.84	51.97	48.67
TiO_2	.07	.60	.35	.18	1.72	.79	.84	1.00	.83
Al_2O_3	13.10	16.58	14.93	13.33	14.04	18.34	18.31	13.52	11.73
Fe_2O_3	1.05	2.55	4.23	1.37	5.63	4.84	4.62	4.74	3.30
FeO		2.92	2.78	1.02	8.69	2.85	3.12	4.08	5.93
MnO	.01	.02	.11	.04	.54	.14	.07	.12	.12
MgO	.06	3.35	4.28	.32	6.43	3.46	3.70	9.62	14.97
CaO	.45	5.00	10.56	1.20	9.12	5.31	6.60	7.91	8.39
Na_2O	3.55	3.91[1]	5.33	3.92	3.24	4.26	3.49	2.01	2.38
K_2O	4.83	2.23	5.27	3.79	1.04	5.22	3.85	4.31	3.06
P_2O_5	.01	.13	1.21	.03	.28	.73	.56	.72	.62
Each sum = 100.00									

[1] Includes .07 per cent. Li_2O.

[2] Includes .05 per cent. Cl and .05 per cent. SO_3.

[3] Includes .02 per cent. Li_2O and .23 per cent. SO_3.

GROUP XVII

	Dike-rocks				
	106	107	108	109	110
No. of analyses	Granite-aplite (Osann, Washington)	Bostonite (Rosenbusch, Washington)	Grorudite (Osann, Washington)	Sölvsbergite (Osann, Washington)	Tinguaite (Osann, Washington)
	15	5	5	8	15
SiO_2	75.00	61.32	70.91	62.16	55.02
TiO_2	.30	.89	.48	.31	.36
Al_2O_3	13.14	18.43	11.50	17.58	20.42
Fe_2O_3	.58	3.84	4.58	3.05	3.06
FeO	.40	1.60	1.88	1.80	1.82
MnO	.07	.01	.39	.18	.22
MgO	.30	.46	.11	.48	.59
CaO	1.13	1.45	.39	1.11	1.67
Na_2O	3.54	5.75	5.43	7.30	8.63
K_2O	4.80	4.94	4.08	4.95	5.38
H_2O	.71	1.31	.25	1.04	2.77
P_2O_5	.03	....	....	.04	.06
	Calculated as Water-free				
SiO_2	75.54	62.14	71.09	62.82	56.59
TiO_2	.30	.90	.48	.31	.37
Al_2O_3	13.23	18.67	11.53	17.77	21.00
Fe_2O_3	.58	3.89	4.59	3.08	3.15
FeO	.40	1.62	1.89	1.82	1.87
MnO	.07	.01	.39	.18	.23
MgO	.30	.47	.11	.49	.61
CaO	1.14	1.47	.39	1.12	1.72
Na_2O	3.57	5.82	5.44	7.37	8.87
K_2O	4.84	5.01	4.09	5.00	5.53
P_2O_5	.03	....	....	.04	.06
	Each sum = 100.00				

GROUP XVIII

Dike-rocks

	111	112	113	114	115	116
	Minette (Osann, Clarke)	Kersantite (Osann, Rosenbusch)	Vogesite (Osann)	Camptonite (Osann)	Monchiquite (Osann)	Alnöite (Osann, Washington)
No. of analyses	10	20	4	15	16	6
SiO_2	49.45	50.79	52.62	40.70	45.17	32.31
TiO_2	1.23	1.02	.54	3.86	1.90	1.41
Al_2O_3	14.41	15.26	14.86	16.02	14.78	9.50
Fe_2O_3	3.39	3.29	3.60	5.43	5.10	5.42
FeO	5.01	5.54	4.18	7.84	5.05	6.34
MnO	.13	.07	.84	.16	.35	.01
MgO	8.26	6.33	8.55	5.43	6.26	17.43
CaO	6.73	5.73	5.86	9.36	11.06	13.58
Na_2O	2.54	3.12	3.21	3.23	3.69	1.42
K_2O	4.69	2.79	2.83	1.76	2.73	2.70
H_2O	3.04[1]	5.71[2]	2.70	5.59[3]	3.40	7.50[4]
P_2O_5	1.12	.35	.21	.62	.51	2.38
Calculated as Water-free						
SiO_2	50.99	53.87	54.08	43.10	46.76	34.93
TiO_2	1.27	1.08	.56	4.09	1.96	1.52
Al_2O_3	14.86	16.18	15.28	16.97	15.30	10.27
Fe_2O_3	3.50	3.48	3.70	5.76	5.28	5.86
FeO	5.17	5.88	4.29	8.30	5.23	6.85
MnO	.13	.07	.86	.16	.36	.01
MgO	8.53	6.71	8.79	5.76	6.48	18.84
CaO	6.95	6.09	6.02	9.92	11.45	14.68
Na_2O	2.62	3.31	3.30	3.42	3.82	1.53
K_2O	4.84	2.96	2.90	1.86	2.83	2.92
P_2O_5	1.14	.37	.22	.66	.53	2.59
Each sum = 100.00						

[1] Includes .61 per cent. CO_2.
[2] Includes 2.61 per cent. CO_2.
[3] Includes 2.97 per cent. CO_2.
[4] Includes 4.35 per cent. CO_2.

INDEX TO TABLE II

Figures refer to column.

Average Specific Gravities

A fundamental datum concerning an igneous rock is its average specific gravity. Unfortunately most authors have neglected to append to each chemical analysis a statement of the density of the analyzed specimen. This is notably the case with the many hundreds of magnificent analyses published by the officers of the United States Geological Survey. It would be a valuable contribution to petrology if the specific gravities of all original analyzed specimens (whole hand specimens) in the collections of that survey and of similar institutions were determined and the results published. Becke has quite recently indicated the importance of such determinations for petrology.[1]

On account of this general failure of record during the last three decades, it is not possible to give satisfactory average specific gravities for most of the holocrystalline igneous-rock types. It goes without saying that rocks containing abundant glass, which from specimen to specimen always varies greatly in relative amount, can rarely give useful averages. However, certain needs in the following discussion are tolerably satisfied by a compilation of the average specific gravities of the plutonic species which have been measured. The more important averages appear in Table III, in which the averages more recently calculated by Becke, from specially selected material, are also entered. In each case the number of specimens averaged is shown in brackets.

[1] F. Becke, Sitzungsber. k. Akad. Wiss., Math. Naturw. Kl., Vol. 120, 1911, p. 265.

TABLE III

	Average Specific Gravity	
	Daly	Becke
Granite,	2.660(58)	2.682(43)
Granodiorite,	2.740(5)	....
Tonalite,	....	2.723(7)
Syenite,	2.773(11)	2.775(27)
Monzonite,	2.805(2)	....
Nephelite syenite,	2.617(10)	2.655(9)
Diorite,	2.861(17)	2.855(13)
Gabbro,	2.933(19)	2.975(27)
Olivine gabbro,	2.948(4)	....
Anorthosite,	2.715(6)	....
Peridotite and pyroxenite	3.176(21)	3.307(13)
Essexite,	2.844(5)	2.915(3)
Theralite,	2.917(3)	2.940(4)
Malignite,	2.884(4)	....

Division According to Mode of Occurrence

Rosenbusch has done special service to petrology and to the theory of petrogenesis in retaining the time-honored division of igneous rocks into the plutonic, volcanic, and dike classes. The separation of the plutonic and volcanic classes is obviously necessary in laying the basis of fact for a general petrogenic discussion. Table II is so arranged as to show a general contrast between those two classes. On the average a plutonic species is less salic, that is, lower in silica and alkalies and higher in iron oxides, lime, and magnesia, than the corresponding extrusive species. The same contrast has been stated by Rosenbusch.[1] It is sometimes illustrated in individual localities where a plutonic rock and the contemporaneous volcanic equivalent have both been discovered and chemically analyzed; but in most cases the characteristic variability of rock-bodies makes it difficult to discern any systematic contrast without a prohibitive number of analyses. In this regard world averages must have special value. An explanation of this fundamental contrast is offered in Chapter XII (page 229). For the present it will suffice to point out that chemical analysis, like the necessities of geological mapping, shows the justice of this old grouping of igneous-rock species.

In spite of recent adverse criticisms, Rosenbusch's conception of the remaining dike class is still the best method of grouping a considerable number of species. Brögger's division of the rock bodies of this class into aschistic and diaschistic is sometimes hard to apply, but its underlying idea is clearly helpful. Aschistic dikes are directly apo-

[1] H. Rosenbusch, Mikroskopische Physiographie der massigen Gesteine, Vierte Auflage, Stuttgart, 1908, p. 717.

physal from larger intrusive masses and have essentially the same chemical composition as these. A diaschistic dike is an offshoot from a larger intrusive mass but represents the effect of more or less thorough splitting or differentiation of that mass, whereby the dike comes to differ chemically from the parent mass.

Igneous-rock Clans

In the index of Rosenbusch's hand-book, more than 660 varieties of igneous rocks are named, and this number excludes many types which, though dignified with special names, are simply weathered or otherwise altered equivalents of species in the first-mentioned group. If there were no obvious genetic or chemical relationships among these hundreds of species, the problem of origins would be, in very truth, a difficult one. However, field and laboratory observations without number have already simplified the problem by showing that the many types can be grouped in chemical series of relatively small number. For temporary, convenient use in this book, these series may be called "clans." Each clan is composed of families, distinguished less by chemical composition than by mode of field occurrence, by mineralogical composition, or by rock structure.[1] The genetic problem is most concerned with the explanation of chemical diversities and it is greatly simplified by recognition of the fact that these clans represent so many chemical groups, each of which includes syngenetic families. For example, the problem of origins is essentially the same for magmas of the syenite family, the syenite porphyry family, and the trachyte family. The chemical similarity of gabbro, gabbro porphyrite, diabase, diabase porphyrite, basalt, dolerite, melaphyre, and other species, suggests, though of course it does not prove, their common magmatic origin. On the other hand, the diorite family, like some other families, includes species which clearly have different lines of descent; but, for convenience of treatment, such a family, together with its effusive and dike equivalents, is here regarded as forming a clan. Thus, while a clan generally represents a group of rocks formed by similar magmatic processes, it may also include some mineralogical and chemical allies formed by quite different processes.

The more important groups are the granite clan, the granodiorite clan, the diorite clan, the gabbro clan, the syenite clan, the nephelite-syenite clan, and the peridotite-pyroxenite clan. The minor groups are the essexite clan, the theralite clan, the ijolite-bekinkinite clan, and the missourite-fergusite clan. The last four groups mentioned,

[1] The term "structure" is here employed with its long-established meaning as used by Zirkel, Rosenbusch, and the majority of petrographers.

together with the nephelite-syenite clan, will be discussed together under the caption "the alkaline clans," in Chapter XX; the other six clans will be treated in as many separate chapters (XV to XIX, and XXI). In those chapters the reader will find lists of the principal rock varieties constituting each of the clans.

CHAPTER III

GENERAL DISTRIBUTION AND RELATIVE QUANTITIES OF IGNEOUS-ROCK SPECIES

Need for Quantitative Study

It is probable that all or nearly all of the clans are represented in each of the seven continents. Most of them are represented in the islands of the great ocean basins, but the granite family seems, according to present knowledge, to be wanting in the islands of the deep seas except in the regions where there is independent evidence of comparatively recent fragmentation and subsidence of former continental areas. The recent attempts to establish a rule localizing the alkaline clans in the "Atlantic" portion of the globe, and the subalkaline clans in and around the "Pacific" region, have not met with general favor among petrologists. Nor has better success attended the attempt to connect the distribution of the alkaline rocks with the type of crustal deformation—foundering or large-scale normal faulting—which specially characterizes the Atlantic basin. The recurrence of most of the clans on every continental plateau and along every ocean border is becoming increasingly evident as the methods of modern petrography are applied to the study of the world's igneous terranes.

Partly owing to this fact, but still more to the circumstance that the rarer rock species are the more "interesting" to most petrographers, the tendency has long reigned in petrographical literature to emphasize the diversity of igneous rocks. Like every other science, petrography has had to be analytic before it could be healthfully synthetic. But there is no little danger of a false perspective if, in the search for specific distinctions, a considerable effort is not made to estimate the actual value of those distinctions. Above all, petrography needs to be ever more closely linked with areal and structural geology, in order that the problem of rock origin may be phrased in terms of the actual proportions of the different species.

Obviously, the data for such a quantitative study of the visible igneous matter in the earth fall far short of being complete enough for the ultimate needs of petrogeny. Yet the documents already published suffice for a few important conclusions from a synthetic study. Certain of these will doubtless stand fast when the whole earth is as well known as the most thoroughly explored parts of Europe or America are now known.

A quantitative review of the myriad facts recorded in petrographic works might, along special lines, be undertaken by such a powerful body as a representative committee of the International Geological Congress. Until that body or a similar group of properly equipped specialists undertakes the great task, it would seem futile for any one to try to state the genetic problem of the igneous rocks in all the fullness and clarity now possible. The writer has found at hand only a few quantitative tests which can be applied to the modern geological maps without a prohibitive amount of labor. Among the significant questions are the following: 1. What are the relative areas of the earth's surface covered by the different intrusive-rock species?

2. How do the respective total areas of the alkaline and subalkaline bodies compare?

3. What is the largest known rock-body representing each of the rock-clans?

Relative Quantities of Igneous-rock Species in the United States

For the petrographer as for the geographer, North America is in many respects "the typical continent." A first approximation to an estimate of the relative areas covered by igneous species throughout the world would be feasible if complete measurements were now at hand for this one continent. Although these can only be made by the work of many future generations, the scanty record of the present day points, with a high degree of probability, to certain principal facts of distribution.

The igneous rocks of North America are almost entirely confined to three provinces, the Pacific Cordilleran system, the Appalachian mountain system (Newfoundland to Alabama), and the pre-Cambrian shield of Canada. In the United States the geology of the Cordilleran and Appalachian provinces has been sampled in the preparation of the folios issued by the Federal geological survey. The number and distribution of these areas are such as to show that the sampling so far accomplished roughly indicates average quantitative relations among the exposed igneous rocks of these two provinces. On the whole, too, the standard of detail and accuracy set for the folios is fairly uniform; in all cases the field conclusions have been checked with more or less thoroughness by microscopic and chemical examinations of the rocks.

The total area of the United States proper is 3,030,000 square miles. Of this, about 159,000 square miles are covered in the folios published up to January 1, 1912. The Cordilleran area is about 800,000 square miles, and in this belt the fifty-nine published folios, in which igneous formations are mapped, cover a total area of 60,990 square miles. The

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Appalachian area is somewhat less than 200,000 square miles; within it the sixteen folios showing igneous formations cover a total area of 13,221 square miles. The writer has measured the total areas covered by each of the igneous-rock species named and mapped in these groups of folios. The results are shown in Table IV.

TABLE IV.—PLUTONIC ROCKS

	Pacific Cordillera, square miles	Appalachian System, square miles	Total, square miles
Pre-Cambrian granite	2089.0	1151.0	3240.0
Paleozoic and later granite	402.0	194.0	596.0
Total granite	(2491.0)	(1345.0)	(3836.0)
Granodiorite	2040.0	....	2040.0
Quartz monzonite	11.0	....	11.0
Quartz diorite	45.3	....	45.3
Diorite	103.5	10.0	113.5
Gabbrodiorite	98.5	....	98.5
Gabbro	226.4	47.5	273.9
Anorthosite	52.0	....	52.0
Syenite	24.4	....	24.4
Monzonite	17.5	....	17.5
Nephelite syenite	3.5	.3	3.8
Shonkinite	8.7	....	8.7
Fergusite	<1.0	....	<1.0
Missourite	.1	....	.1
Theralite	6.3	....	6.3
Peridotite	73.3	....	73.3
Pyroxenite	2.2	....	2.2
Totals	5204.7	1402.8	6607.5

"HYPABYSSAL ROCKS" (INTRUSIVE)

	Pacific Cordillera, square miles	Appalachian System, square miles	Total, square miles
Granite porphyry	17.9	2.0	19.9
Quartz porphyry and rhyolite	26.5	1.0	27.5
Dacite porphyrite	7.8	....	7.8
Quartz-hornblende porphyrite	2.0	....	2.0
Quartz monzonite porphyry	4.6	....	4.6
Diorite porphyrite	20.1	1.6	21.7
Hornblende porphyrite	1.0	....	1.0
Quartz diabase	3.0	....	3.0
Diabase	150.0	118.0	268.0
Syenite porphyry	38.4	2.5	40.9
Monzonite porphyry	9.4	....	9.4
Nephelite syenite porphyry	< .1	....	< .1
Phonolite	2.7	....	2.7
Pseudo-leucite porphyry	.5	....	.5
Totals	284.0	125.1	409.1

EXTRUSIVE ROCKS

	Pacific Cordillera, square miles	Appalachian System, square miles	Total, square miles
Rhyolite	2145.7	1.0	2146.7
Dacite	82.1	....	82.1
Mica andesite	3.0	....	3.0
Hornblende andesite	21.6	....	21.6
Pyroxene andesite (chiefly)	3966.0	....	3966.0
Augite porphyrite	255.0	....	255.0
Basalt	3079.0	130.0	3209.0
Trachyte	6.5	....	6.5
Latite	4.6	....	4.6
Phonolite	5.5	....	5.5
Trachydolerite	.3	....	.3
Teschenite	.2	....	.2
Nephelite basalt (Texas)	1.2	....	1.2
Nephelite-melilite basalt (Texas)	2.8	....	2.8
Limburgite	2.5	....	2.5
Quartz basalt	8.0	....	8.0
Totals	9584.0	131.0	9715.0
Total igneous-rock area mapped.	15,072.7	1,658.9	16,731.6

The measurements for each sheet were not made with extreme nicety, for that would have involved much labor useless for present purposes. However, the order of magnitude is believed to be correctly stated. The areas of the rock types showing small extension were measured with special care. Composite terranes, respectively including several igneous species but mapped under one color, were neglected. In some cases terranes of greatly altered igneous rocks were similarly excluded from consideration.

In estimating the relative volumes corresponding to the areas listed, it should be noted that many of the bodies of "plutonic rocks" are really sheets, laccoliths, or irregular intrusions, and hence do not extend to great depths. This is true, for example, of all the theralite mapped, of some diorites, and of many shonkinitic, monzonitic, and syenitic bodies. It is not certain that any of the gabbro masses extends, with undiminished length and breadth, to a depth of more than a few thousand feet. On the other hand, most of the granite, granodiorite, and quartz diorite bodies have depths to be estimated in miles. Hence, several of the plutonic types, which show small total areas, are yet more clearly subordinate in respect of total volume.

Again, observation shows that for the effusive types small total area is generally accompanied by small average thickness.

Hence, whether we compare the plutonics *inter se* or the effusive rocks *inter se*, the volumes of the less extensive eruptives in the folio quadrangles are likely to have even lower ratios to the volumes of the other eruptives than those between their respective surface areas.

Relative Abundance of the Alkaline Rocks, Including the Syenite Clan

The "alkaline provinces" of the Cordilleran belt include some which are among the most extensive in the world and are also very rich in types. In this part of the world the shonkinites, missourites, fergusites, theralites, and latites were first named and described. Perhaps in no other region are the monzonites represented by more numerous distinct bodies than in the United States portion of the Cordillera. There is no reason for believing that the relative abundance of the alkaline rocks in the Cordillera as a whole is greater than that illustrated in the Cordilleran quadrangles of the Geological Survey folios so far published.

Hence, the following conclusions directly derivable from Table IV are highly significant. The combined area of all the syenites, nephelite syenites, monzonites, shonkinites, missourites, fergusites, and theralites of these Cordilleran quadrangles is only about 61 square miles out of a total of the 5205 square miles covered by all the plutonic types mapped in these quadrangles. The combined area of the syenite porphyries, monzonite porphyries, nephelite-syenite porphyries, pseudo-leucite porphyries, and intrusive phonolite is only 51 square miles out of a total of 284 square miles of hypabyssal rocks. The combined area of the extrusive trachytes, latites, trachydolerites, phonolites, teschenites, nephelite basalts, and limburgites is only about 23 square miles out of a total of 9584 square miles of extrusives. The combined area of all the mapped alkaline rocks (including syenites and trachytes) in the Cordilleran quadrangles is only about 135 square miles out of a grand total of about 15,000 square miles of igneous rocks.

The totals for the alkaline rocks will doubtless be enlarged as more detailed petrographic work is done in the Cordillera, but it seems certain that all totals for this group of rocks must, in this vast belt, always remain extremely small as compared with the totals for the subalkaline types.

The sixteen Appalachian folios show only 0.3 square mile of nephelite syenite and 2.5 square miles of syenite porphyry to represent the entire alkaline group of rocks (including syenites and trachytes), although 1659 square miles of igneous rocks are mapped in these folios.

In all the folios the combined area of all mapped alkaline rocks is about 140 square miles out of 16,700 square miles of igneous formations mapped.

Considering the relatively small thickness represented in most of the alkaline bodies mapped in these folios (sheets, laccoliths, lava flows, beds of pyroclastics), it is tolerably certain that the total maximum volume of alkaline rock exposed in these quadrangles is far less than one-half of 1 per cent. of the total maximum volume of subalkaline rock.

The same truth is to be inferred from a general review of North American petrographic geology. Including the large syenite, nephelite syenite, and malignite masses mapped in New York State (150 square miles), New Hampshire (21 square miles), Ontario (100 square miles), and British Columbia (200 ± square miles), the total area of alkaline rocks (including syenites) actually mapped in North America, outside the United States Geological Survey folio quadrangles, is slightly over 500 square miles. In all, then, about 700 square miles of alkaline rocks have been mapped on this continent.

In the Cordilleran belt there are about 170,000 square miles of post-Cambrian plutonic rocks indicated on the new map of North America published by the United States Geological Survey, 1911. These rocks are chiefly granodiorites and granites. In the same belt over 400,000 square miles of post-Cambrian volcanic rocks are shown on the map; most of the extrusive bodies are basalts and the rest are chiefly basaltic andesites.

In the Appalachian mountain system the same map shows about 30,000 square miles of post-Cambrian extrusives, which are known to be almost entirely subalkaline and chiefly granitic.

The post-Cambrian intrusives and extrusives of this continent are known to cover total areas whose orders of magnitude are, respectively, 200,000 square miles and 400,000 square miles. It is safe to say that the pre-Cambrian granites (with the orthogneisses) cover at least 1,000,000 square miles.

We may conclude that all the known alkaline rocks of North America (including the syenites and monzonites) have a total area less than .05 per cent. of the total known area of the igneous rocks. In view of the striking field appearance of most of the alkaline types and in view of their superior "interest" for petrographic geologists, one may readily believe that these rocks are somewhat over-emphasized in the existing maps and memoirs. The sampling of this continent so far accomplished indicates, in fact, that its visible alkaline bodies have a total volume probably less than one-tenth of 1 per cent. of the total volume of its visible subalkaline bodies.

A partial canvass of the geological maps of Europe has convinced the writer that the corresponding ratios for that continent are of the same order of magnitude. Without exception the large-scale maps of European countries are much less satisfactory in a study of this kind than are the folios of the United States Geological Survey. The writer found that the time and labor required to assemble the maps and memoirs and to weigh them properly, so as to allow for variable petrographic standards, etc., were practically prohibitive. It is much to be desired that quantitative studies of the igneous terranes be undertaken by each geological commission in Europe.

The number of alkaline bodies in Europe is large, but, with a few exceptions, they are all very small. Though phonolite was first named in Germany, the eye is much strained to find the tiny spots of color for phonolite on Lepsius's wonderful map of the empire. The Tertiary nephelite basalts, melilite basalts, and limburgites are exceptionally well developed in Germany, but, taken together, they are probably far inferior in volume to the ordinary plagioclase basalts; and, in any case, cannot be compared in inferred volume with the pre-Tertiary eruptive rocks of the empire. Though trachyte was first named in France, neither this well-known species nor phonolite could be profitably shown with separate color on the new, beautiful wall-map of France published by the government survey. Inspection of that map or of the large-scale sheets of the French survey will readily indicate to the reader that the total volume of the French alkaline bodies must be much less than 1 per cent. of the combined subalkaline bodies in that country. A similar statement may be made for Great Britain and Ireland, for Switzerland, for Finland, and for Spain. In Scandinavia, Italy, and perhaps Portugal, the alkaline rocks are relatively more voluminous, but it is questionable that, in any one of these countries, they have a total volume which is 5 per cent. of the total for the subalkaline bodies.

For Europe as a whole the writer suspects that this ratio is less than one to one hundred.

Though so little is known of Asia, Africa, Australia, and Antarctica, it seems highly probable that for each of these continents the ratio is again less than one to one hundred; in fact, there is nothing to indicate that it is greater than one to one thousand.

Whatever criticism may be advanced against this "extrapolation" from so incomplete a body of known facts, a definite conclusion on this matter is already clear. The ratio of volumes is certainly extremely small for North America and there is no reason to doubt that this continent is a fair sample of all the lands of the globe. When it is further remembered that the number of known localities for the alkaline rocks has been greatly and specially increased during more than thirty years of enthusiastic search, we are prepared for the view that the alkaline clans, taken together, are, as it were, only incidental products of a planet whose eruptions have been overwhelmingly of the subalkaline quality. The significance of this basal fact will be noted in Chapters XIX and XX.

Relative Abundance of the Subalkaline Clans

Returning to Table IV, the reader will observe significant quantitative relations between the diorites, gabbros (including gabbrodiorites and anorthosites), and peridotites on the one hand, and granite and granodiorite on the other.

Though the first three plutonics named are found in a large number of distinct bodies, their total areas in the folio quadrangles are respectively less than 4, 10, and 2 per cent. of the total area of granite; and respectively less than 6, 19, and 4 per cent. of the total area of granodiorite. Like the many alkaline species as a whole, each of these basic plutonic types is quantitatively very subordinate to the acid types. A review of the maps and memoirs concerning other parts of North America, as well as the other continents need not be absolutely complete to convince one that diorite, gabbro, and peridotite, either singly or collectively, have, when compared to granite and granodiorite, subordinate place in the world's terranes; the ratio of their total areas, over the whole earth, will have the same order of magnitude as that deduced from the United States folios. In principle this statement is obvious to any informed petrographer, but the figures will tend to keep these fundamental facts always in view as the genetic problem is discussed.

Equally evident and equally important is the fact that the *extrusive* members of the basic subalkaline clans excel the extrusive members of the granite and granodiorite clans, both in total areas and in average thicknesses. It may be observed that the United States folios cover most of the Yellowstone rhyolite plateau, almost certainly the greatest body of this type of lava in the world. A fairer estimate of the true relative areas would be gained by deducting the 1750 square miles of rhyolite recorded in the Yellowstone Park folio. If, however, this rhyolite be retained in the total, and if there be added to it the enormous areas of basalts and andesites in the part of the Cordillera not covered by the folios, the relative insignificance of the volume of acid lavas, as compared with that of the basalts or with that of the basic andesites, is made even clearer. It is questionable that the total volume of the visible rhyolites of North America is as much as 1 per cent. of the total volume of the visible basalts or that of the visible basic andesites. The writer believes, though on less secured evidence, that the same order of magnitude characterizes the ratios for the rest of the world.

These general conclusions may be conveniently illustrated in tabular form:

Ratio of total area of world's granite to total area of world's diorite.	>	$\frac{20}{1}$
Ratio of total volume of world's rhyolite to total volume of world's andesite	<	$\frac{1}{10}$
Ratio of total area of world's granite to total area of world's gabbro	>	$\frac{20}{1}$
Ratio of total volume of world's rhyolite to total volume of world's basalt	<	$\frac{1}{50}$

Though the exact figures of this table are, of course, now impossible of verification, they serve to indicate one of the most vital facts in petrology. The basic subalkaline clans predominate in the extrusive phase of igneous action; the acid subalkaline clans predominate in its intrusive phase.[1] This indubitable fact needs explanation and, in the writer's opinion, that explanation must be at the very heart of a general theory of petrogenesis.

Rock Species known only in Extremely Small Areas or Volumes at the Earth's Surface

Out of the ten families of plutonic rocks discussed in Rosenbusch's hand-book (4th edition), four families are but feebly represented among the world's terranes as known at the present time. The total known area of the bodies corresponding to each family is very probably less than 50 square miles. A closer statement of their respective known quantities is:

Family		Superior limit of known total area
Essexites		50 square miles.
Shonkinites and Theralites	Shonkinites (largely sheets and laccoliths)	20 square miles.
	Theralites (largely sheets and laccoliths)	20 square miles.
Missourites and Fergusites	Missourites	1 square mile.
	Fergusites	1 square mile.
Ijolites and Bekinkinites	Ijolites	5 square miles.
	Bekinkinites	1 square mile.

[1] Though plutonic and effusive representatives of the granite clan are extremely abundant in Fennoscandia, Sederholm states that "it is astonishing not to find any abyssic rocks certainly connected with the rocks of the diabase which have erupted during every time of quiet sedimentation in Fenno-Scandia, either forming effusive beds, or being intercalated between the strata of the sediments." (J. J. Sederholm, Bull. Comm. géol. Finlande, No. 22., 1907, p. 108.)

A close quantitative view of the dike-rocks is, of course, impossible, but, on the average, no type in this class of rocks is likely to have a total volume as much as 5 per cent. of the volume of its parent plutonic chamber. For most of the species the ratio is probably less than 1 : 100. These figures, as well as the actual field relations, show that the genetic problem of the dike-rocks is largely bound up with the problem of the plutonic masses.

Difficult as it is to obtain an idea of the volume of plutonic bodies from the surface outcrop, it must be at least as impracticable to estimate the true volumes of the world's extrusive masses, each of which is of ever-varying thickness. Of the fourteen families listed in Rosenbusch's hand-book, eleven families represent rock masses now known only in small total volumes respectively, as compared with the family of basalts (melaphyre and diabase). The family of andesites and porphyrites may have a total volume of the same order of magnitude as that of basalt. The family of the "quartz trachytes and quartz porphyries" (including rhyolites) comes next to those two families in respect of total known volume, but is clearly quite subordinate to them, as already indicated. No one of the other eleven families is known to have a total volume as much as 1 per cent. of the basaltic masses already demonstrated on the globe. The families of relatively small total volumes may be listed as follows:

Trachytes and quartz-free porphyries.
Phonolitic rocks.
Dacites and quartz porphyrites.
Picrites and picrite porphyrites.
Trachydolerites.
Tephrites and basanites.
Leucite rocks.
Nephelite rocks.
Melilite rocks.
Limburgites and augitites.
Lamprophyric effusive rocks.

Summary of Conclusions regarding Relative Abundance

All of the above-mentioned estimates are phrased in terms of the total volumes of the rock masses actually mapped and studied by modern petrographic methods. They are all, of course, subject to the criticism that future work may tend to increase the relative volumes of the subordinate families. This is likely to be the case with the extrusives, though the writer believes that the orders of magnitude represented in the foregoing estimates will always apply. An attentive study of petrographic literature, as it issues from the press year by year, shows that new discoveries do not tend to alter the position of the rock families noted above as dominant in the world. This is true, notwithstanding the tendency of petrographers to publish material concerning the rarer types and to neglect the others. As already noted, this psychological factor has thus long tended to place misleading emphasis on the qualitative side of petrology. The more objective product of the great government surveys is a useful corrective to this tendency. For this reason, the writer has laid special stress on the work of the United States Geological Survey, the Geological Survey of Canada, and the surveys of Western Europe, where the microscope and chemical analysis have been systematically applied. The assumptions are here made: that each survey has fairly sampled its territory, giving a picture of the average quantitative relations of the rock in each country; and that North America and Europe are, in their turn, fair samples of the whole area of the continental plateaus. These assumptions are already so well founded on recorded facts that certain generalizations seem to be unshakable, even though they are built on limited exact knowledge concerning the earth.

1. The visible alkaline rocks of the world (including the syenite and monzonite clans) probably have a total volume less than 1 per cent. of that of the visible subalkaline rocks (granite, granodiorite, diorite, gabbro, and peridotite clans).

2. Among the visible intrusive rocks, the granites and granodiorites together have more than twenty times the total area of all the other intrusives combined.

3. Among the visible extrusive rocks, basalt has probably at least five times the total volume of all the other extrusives combined; basalt and pyroxene andesite together have at least fifty times the volume of all the other extrusives combined.

4. The granite clan is highly predominant among the intrusives and is one of the more subordinate clans represented in the extrusives.

5. The diorite clan is decidedly subordinate among the intrusives but rates next to the gabbro clan among the extrusives.

6. The gabbro clan is likewise subordinate among the intrusives, but distinctly predominates among the extrusives.

7. Quantitatively considered, the igneous rocks of the globe chiefly belong to two types, granite and basalt. This truth was long ago recognized by Durocher, von Cotta, and Bunsen, and later by Michel Lévy, Loewinson-Lessing, and others. But petrologists have still to become unanimous in fully appreciating that the one of these dominant types is intrusive, and the other extrusive. To declare the meaning of this fact is to go a long way toward outlining petrogenesis as a whole.

Maximum Size of Individual Bodies

To visualize the genetic problem ideally it would be further necessary to know the average size of the rock bodies corresponding respectively to the intrusive and extrusive members of each of the great clans. For obvious reasons this is now impossible even for the thoroughly mapped regions of the earth. However, it is well to supplement the foregoing statements of relative quantities by an estimate of the actual areas covered at the earth's surface by the representative largest known masses of the important intrusive types.

TABLE V

Rock type	Location of rock bodies (intrusives)	Area in square miles
Granite (pre-Cambrian)	Post-Bottnian "central" granite of Finland.	9,100
Granite (post-Cambrian) (laccolith).	Bushveldt, Transvaal	10,000 ±
Granodiorite	Sierra Nevada	20,000 ±
"Quartz monzonite"	Bitterroot Range, Idaho	3,000 ±
Quartz diorite (tonalite)	Southern Alaska	5,000 ±
Diorite (stock)	Little Belt Quadrangle, Montana	25
Gabbro (laccolith)	Duluth and northeastward, Minnesota	2,400
Anorthosite (laccolith?)	Saguenay district, Quebec[1]	5,800
Peridotite	Mt. Stuart Quadrangle, Washington	40 +
Pyroxenite	Mt. Diablo, California	2
Subalkaline syenite	Ceará, Brazil	500 ± (?)
Pulaskite	Coryell batholith, West Kootenay district, British Columbia.	100
Nordmarkite	Nordmarken, Norway	800 ±
Nephelite syenite (laccolith?).	Kola peninsula, Lappland	700 ±
Laurvikite	Laurvik, Norway	250 ±
Malignite	Pooh Bah lake, Ontario	15
Monzonite	Telluride Quadrangle, Colorado	8
Essexite	Shefford Mountain, Quebec	1.5 +
Shonkinite (laccolith)	Square Butte, Montana	4
Missourite (stock)	Shonkin stock, Montana	$<$ .7
Fergusite (stock)	Arnoux stock, Montana	$<$1
Theralite (laccolith)	Northern Crazy Mts., Montana	4
Ijolite	Kuusamo parish, Finland	$<$1.0(?)
Bekinkinite	Bekinkina Mts., Madagascar	1.0(?)

This table also emphasizes the relative insignificance of the alkaline rocks; the clear dominance of the more silicious types among plutonic bodies; and the subordinate place of basaltic (gabbroid) magma in the world's intrusions.

General Remarks

Two of the laws of distribution are truisms to geologist and petrographer. Magma of basaltic composition is clearly the most

[1] An area east of the Moisie River, Quebec, is estimated to cover 10,000 square miles, if mapped correctly.

widespread, occurring in plains, in mountains, and in all of the ocean basins. Granites, granodiorites, and most diorites are continental rocks and, more specifically, mountain rocks.

Petrographical provinces exist, but one such province may be more or less closely duplicated in another continent or ocean basin. The rock types found in the Monteregian Hills, Quebec, correspond in many essential details with those of the Adirondacks, of Mount Ascutney, Vermont, or of the Christiania Region, Norway. The special combination of anorthositic and syenitic species in the Adirondacks is remarkably like that of western Norway. The rock associations of the Bohemian alkaline province are more or less fully repeated at the Great Rift of Africa, in central France, in Tahiti, in the Canary Islands, in the Azores, in Hawaii, etc. Many more examples will be noted in the following chapters. They all go to show that the petrogenic mechanism has worked in practically the same manner beneath each of the continents and, with exceptions to be further discussed, beneath each ocean basin. Sameness in the midst of variety is a principal result of the earth's igneous activity.

This fundamental fact is obscured by belief in the existence of "Atlantic" and "Pacific" branches into which igneous rocks are to be divided. The inappropriateness of these terms is manifest from many considerations already dealt with by different writers; little need be added on the present occasion. (See pages 338 and 412.)

CHAPTER IV

ERUPTIVE TYPES AND THE GEOLOGICAL TIME SCALE

Eruptive Sequences

Having obtained at least a limited view of the space relations of igneous rocks we now turn to the subject of their time relations. To bring illustration of the essential facts within practical limits the writer has constructed Table XXI (Appendix B).

The table is intended to be representative of the many thousand sequences actually determined for local areas of the world's igneous rocks. The first part exemplifies the pre-Cambrian succession of those rocks. The second part states the case for typical districts where the order of eruption is known for the pre-Cambrian as well as for the later periods. The third part relates to eruptive sequences occurring only in post-Cambrian time. Some of the sequences refer to igneous development in whole countries, like the British Isles or Germany; others refer to very small areas, like the Eolian Islands or the single island of Vulcano. Either kind of statement, supported by the detailed facts of the original monographs, has its special value in petrogenic theory.

The order of eruption is indicated partly by the geological dates, and in all cases the statement begins with the oldest eruptive. Within a given geological period the order is shown by numerals. In some instances a half-dozen or more types are referred to the same geological period, without any note as to the relative ages of those types. Generally this means that information on such a group is lacking; much more rarely it means that the eruptions are known to be essentially contemporaneous.

In an extensive region affected by igneous action, the eruptions generally, if not always, form groups which are separated in time by long intervals. The intervals may be one or more of the standard geological periods, like the Triassic or the Eocene; or they may be separated by a long epoch of erosion. For example, the twenty-five rock species listed in the Upper Huronian and Keweenawan of the Lake Superior district were erupted after the development of the peneplain of the "Eparchean Interval." During so long a time as that represented in peneplanation, the magmas which had been injected into the earth's crust must have crystallized to a depth of several miles below the roofs of their chambers (dike, stock, or batholith).

As shown in Chapter IX, all basic eruptives at least are due to injection of the crust from beneath. This was undoubtedly the case with the dominant magma erupted after the close of the "Eparchean Interval." Similar crustal injection occurred in the Lake Superior district at least twice before this peneplanation. The visible igneous rocks of the region are, therefore, to be referred to at least three *petrogenic periods or cycles.* Many of the series in Table XXI also show long time intervals during which igneous action was dormant. The positions of these time-gaps are indicated by solid lines in the table. The gaps have there been recorded conservatively, so that the total number of petrogenic cycles indicated is a minimum.

Recurrence of Types Belonging to the Gabbro Clan.

The chemical type most often represented in past eruptions is the basaltic. In North America the oldest recognized igneous formation, the Keewatin, is largely a greenstone, originally of basaltic composition. In Europe the oldest recognized members of the "Archean" contain "metabasites" of similar original nature. There is no younger igneous rock on the globe than the basalt which at this moment is splashing and solidifying in the crater of Kilauea. This already well known fact, the persistence of the basaltic type in past eruptivity, is illustrated in Table XXI. Gabbro, diabase, basalt, or their chemical equivalent appears in 56 of the 62 series listed in the table; and in 96 of the 116 different petrogenic cycles there indicated. This type of magma is recorded in the rock group initiating the sequence for each of 68 cycles.

The immediate areas covered by the named authors dealing with the Belknap Mountains and Red Hill of New Hampshire, with the Goldfield district of Nevada, with the Ouray-Silverton quadrangles of Colorado, and with the trachytic areas of the Carpathian Mountains, have no stated outcrops of rock belonging to the gabbro clan. In each of these tracts, however, such rocks appear at distances of a few miles from the limits of the tract. It is, in fact, highly probable that for any area as large as the state of Massachusetts (8,000+ square miles), the eruptive sequence includes rocks referable to the gabbro clan.

Further, the geological record shows that, from an early pre-Cambrian epoch to the present, basaltic lavas have been extruded not only the most often but also always in the greatest average volume, during any one of the longer divisions of the time record. This statement is obvious to any informed worker with the world's geological maps. Sufficient evidence for its truth is the long list of dated fissure eruptions to be found in a later paragraph of this chapter.

The masses formed by such eruptions are overwhelmingly basaltic and are almost always greater in volume than the other volcanic masses of the same geological period.

On the other hand, the intrusive members of the gabbro clan, in the pre-Cambrian and in each of the following geological periods, have always been subordinate to the granites. Thus, the dominant intrusive type has always been granite, while the dominant extrusive type has always been basalt. We have already found the same important relation registered in the present distribution of igneous rocks, regardless of age.

General Recurrence of Other Clans

Supplementing the information contained in Table XXI with that embodied in the thousands of modern geological maps and memoirs, a general conclusion regarding rock types other than basalt and its chemical equivalents, becomes apparent.

Excepting the missourite-fergusite and theralite clans, all the clans are represented by eruptives in both pre-Cambrian time and in Cenozoic time. The two clans named are not shown to be represented among the pre-Cambrian eruptives, but their discovery in that oldest terrane may be made at any time, and in any case these clans are of almost negligible quantitative importance in the record of igneous rocks now determined for all the geological periods. Thus, in the first of the greater divisions of geological time, as in the last division, the eruptives were of the same quality. Similarly, most of the clans, including all the dominant ones, are also represented in the Paleozoic eruptive bodies and in the Mesozoic bodies. An ultimate theory of the igneous rocks must, therefore, recognize a mechanism which has produced eruptions of each of the principal chemical types at intervals from at least later pre-Cambrian time to the present time.

Time Relations of the Granite, Diorite, and Granodiorite Clans. —Yet, for some of the clans, nature has varied the accent in the record of earth history. Regarding area alone, more than nine-tenths of the world's granite (including orthogneisses, excluding the granodiorites) is pre-Cambrian in date. Allowing for the pre-Cambrian granites underlying the later sediments, this fraction is likely to be nearer ninety-nine one-hundredths.

Notwithstanding the enormous erosion which has affected the pre-Cambrian terranes, they are also specially rich in the effusive representatives of the granite clan. The visible roots of the pre-Cambrian (extrusive) leptites and quartz porphyries in Fennoscandia and of the similar types in the Canadian shield have total area and inferred volume so great as to imply special intensity of rhyolitic eruption in the pre-Cambrian.

In spite of the incompleteness of petrographic surveys it seems fairly probable that the visible masses belonging to the granodiorite clan (including many quartz monzonites and quartz diorites) are chiefly of post-Cambrian dates.

Throughout post-Keewatin or post-Bottnian time, the intrusive members of the diorite clan seem always to have been very subordinate in volume. On the other hand, the effusive members of this clan, represented by many porphyrite and greenstone masses of pre-Cenozoic age, as well as by the less altered andesites, have very generally rated next to the basalts in average volume, if not in frequency of eruption.

Time Relations of the Alkaline Clans.—Jensen has recently argued that the alkaline rocks of the world are almost entirely of Tertiary dates.[1] In view of the multiplying discoveries of pre-Tertiary nephelite syenites, malignites, monzonite, etc., this statement must be seriously qualified. It is only natural that the pre-Tertiary alkaline masses, because always of relatively small volumes, should have been destroyed or greatly diminished by Tertiary or earlier erosion, or else completely buried under Tertiary or older sediments. Nevertheless, it may still be a fact that the Cenozoic era was a time for the special development of alkaline eruptives, both in breadth of geographical distribution and in total volume.

Special Time Relation of Anorthosite.—Anorthosite represents the one plutonic type whose eruptions seem to be more or less definitely confined to one part of geological time. By far the greatest amount of this rock constitutes masses of pre-Cambrian date. So far, the writer has discovered in the literature references to only one region where anorthosite of post-Cambrian date has been found on any notable scale. That is the region of the Norwegian anorthosites described by Kolderup, who refers them to a late Silurian or post-Silurian epoch. Since this type is so conspicuous in the field, its recurrence in the pre-Cambrian and its very small volume in the younger terranes is not to be explained as due to the accidents of geological discovery. The problem of origins must, then, take account of this relation of the anorthosites to geological age. (See Chapter XV.)

Dike-rocks in Geological Time.—What has been stated regarding time relations of the clans in general will, of course, apply to the aschistic dike-rocks. The diaschistic types need a special induction. This cannot yet be carried out with even that degree of completeness possible for the principal clans. The exact dating of dikes in the geo-

[1] H. I. Jensen, Proc. Linn. Soc., New South Wales, Vol. 33, 1908, p. 491.

logical record is generally more difficult than that of the larger intrusive masses. Moreover, it is only within the last twenty-five years that much attention has been given to the "complementary" dikes.

So far, the diaschistic dikes known to be of pre-Cambrian age are almost wholly aplites and pegmatites. A malchite from the Marquette district of Michigan and a tinguaite (heronite) from Ontario are other pre-Cambrian dikes of this class noted by Rosenbusch in his handbook. A few other types, including the camptonite, alnöite, monchiquite, and tinguaite, of Alnö, Sweden, may date from the late pre-Cambrian, but absolute certainty on that point is not yet assured. Thus, in spite of the enormous development of igneous rocks in the oldest terrane, diaschistic dikes other than the commonest kinds, granitic aplites and pegmatites, seem to be very rare in it. The rock types which are known only, or almost wholly, in post-Cambrian representatives are: paisanite, bostonite, gauteite, sölvsbergite, minette, kersantite, vogesite, odinite, cuselite, spessartite, fourchite, and ouachitite. The many expert petrographers who have ranged widely over Fennoscandia, the Canadian shield, the Adirondacks, the numerous pre-Cambrian areas of the North American Cordillera, the peninsula of Hindustan, and other smaller areas of the ancient terrane, have certainly not been oblivious to the attraction which diaschistic dikes have long had for workers in the younger rocks. On the contrary, it appears safe to hold that these particular dike-magmas have been chiefly developed during post-Cambrian time.

Modes of Eruption and Geological Time

As shown in Table VI, page 98, intrusion of the batholithic type has been recorded in the pre-Cambrian (at least three distinct epochs), at the close of the Ordovician(?), and in the Devonian, the Carboniferous, the Jurassic, the Early Tertiary, the Miocene, and (probably) the Pliocene. Each of the major geological periods has doubtless witnessed the injection of dikes and of sills or laccoliths, as well as volcanic eruptions of the central type. Fissure eruptions of basaltic magma were incidents in the history of many periods, as illustrated in Table X, page 191.

It is generally agreed that the pre-Cambrian was an era of specially extensive and prolonged batholithic intrusion. Of late years evidence has accumulated that it was also a time of intense vulcanism. Gigantic fissure eruptions and pyroclastic developments then formed many basaltic masses which are probably without parallel among later formations. In Chapter XV the probability is stated that the enormous gabbro and anorthosite bodies of the pre-Cambrian are of laccolithic origin. If that be true, it follows that conditions were extraordinarily favorable for the transfer of these magmas into the stratified terranes. Moreover, the *lit par lit* injection of acid magma is an amazingly persistent feature of the British Columbia pre-Cambrian and the writer has come to suspect that some of the so-called batholiths of other Archean areas are really thick sills. In brief, igneous action in all its principal phases peculiarly characterized the pre-Cambrian era not only as regards persistence in time and wide extension in space, but also with respect to the scale of the magmatic movements.

Summary

Incomplete as induction must be at the present day, certain general conclusions appear to be justified.

1. In a qualitative way the intermittent development of igneous-rock bodies through the geological record has followed uniformitarian lines. In their chemical diversity as in their modes of eruption, the visible pre-Cambrian, Paleozoic, and Mesozoic bodies are, in general, similar to the corresponding Tertiary types.

2. Exceptions to these rules are to be found: (a) in the excessive development of true granites in the early pre-Cambrian; (b) in the restriction of all important masses of anorthosite to pre-Devonian, and usually pre-Cambrian, dates of eruption; (c) in the special development of alkaline rocks and of the granodiorite clan in post-Cambrian, especially post-Paleozoic, time; (d) in the special diversification of diaschistic dikes in post-Cambrian time; (e) in the special strength of the earth's eruptivity—batholithic, volcanic, and laccolithic—during the pre-Cambrian. The explanation of these certain or highly probable facts are so many items in the petrogenic problem.

CHAPTER V

INJECTED BODIES

Classification of Intrusive Bodies

To complete the summary of the facts which it is the duty of any petrogenic theory to explain, it is necessary to review the types of form assumed by igneous rocks. These types almost always show some degree of transition into one another. An intrusive sheet or laccolith is generally continuous with its feeding dike or dikes. Many sheets, laccoliths, or dikes communicate with their parent batholiths. Even the distinction between intrusive and extrusive bodies is occasionally difficult to make in the field, where, for instance, a dike passes at the top into a lava flow, or where the material of a batholith is poured out on the surface. Nevertheless, the existence of such transitional phases cannot affect the supreme value of a classification of igneous masses on the basis of their forms and field relations.

On account of their greater volume and higher importance in petrogenesis, the intrusive bodies will be here treated before the extrusive bodies. In 1905 the writer published a paper on the classification of the intrusive bodies. A scheme was there outlined which seemed to combine the best elements of geological tradition on this subject. The reader is referred to the paper itself for a statement of the grounds on which the classification and corresponding definitions are based.[1] The needs of this book will be met by a brief statement of the definitions, accompanied by fuller illustration of the world's intrusive masses. Some paragraphs of the 1905 paper will be quoted.

The general adoption of a consistent, well-defined scheme of types—a scheme as complete as possible, but elastic enough to admit of new types—would tend to make field descriptions more scientific than many of them are at present. Such general adoption would mean a gain in precision, in the ease with which a description of igneous intrusions would be understood, and in an economy of words. The filling-out of the scheme of classification to an extent quite beyond that now prevailing in standard text-books of geology would further have the effect of sharpening the eyes of the field observer. He may perhaps not be content to describe a given granite intrusion as simply a "mass," or an "area," or an "outcrop," if it be possible by the study of its

[1] R. A. Daly, Jour. Geology, Vol. 13, 1905, pp. 485–508.

contacts to indicate the real form and relations of the granite body. The use of the term "mass" in that sense is often excellent because of the apparent impossibility of determining the true shape of the granite body; but such justifiable employment of the term implies that that particular body cannot as yet be thoroughly classified. A rather negative name has in such a case a distinct value. Of yet greater value is the positive reference of intrusive bodies to definite categories. A good observer always feels the pressure of the category. If his classification be systematic, his observing power is quickened, his report enriched; if his classification be that in general use, his descriptions will be of the greater service to the science.

For a given body the method of intrusion is the most important criterion that could be used in classification. If it might be determined in every detail just how the igneous mass reached its present position, the form of the body and its relation to structural planes in the country rock would therewith be known. A genetic, and therefore natural, classification would thus be founded on the method of intrusion. In the present state of geological science it is, however, impossible to apply this fundamental principle throughout the established list of intrusive bodies.

The greater number of recognized types are those of bodies of magma which is exotic except for a small, variable portion of it due to contact fusion. In each of these cases the magma has come into its chamber through channels which have fed the growing body from larger, deeper-lying, generally invisible reservoirs. The chamber is due to a parting of the country rock into which the magma is injected. An injected body is thus one which is entirely inclosed within the invaded formations, except along the relatively narrow openings to the chamber where the latter has been in communication with the feeding reservoir.

On the other hand, stocks, bosses, and batholiths never show a true floor. They appear to communicate directly with their respective magma reservoirs. Each of these bodies shows field relations suggesting that it is a *part* of its magma reservoir and that communication with the magmatic interior of the earth is not established by narrow openings, but by a huge, downwardly enlarging opening through the country rock. In relation to the invaded formations a stock, boss, or batholith is intrusive, but is *subjacent* rather than injected.

How a batholithic reservoir is enlarged along its contacts is a matter permitting as yet of no absolute certainty. In separating intrusive bodies into two primary divisions, one including all injected bodies, the other including subjacent bodies, a classification will do good service in emphasizing the need of further investigation into the mechanics of intrusion. No one has yet proved that any granite mass over 200 square kilometers in area and characterized by vertical or outwardly sloping contact surfaces, is due to injection. Whatever may be the probabilities, all geologists are not agreed that such a mass has been intruded by any kind of assimilation of the invaded formations. Some light has been shed on the origin of batholiths and stocks, but they are certainly not understood as are dikes and sills.

So far as the method of intrusion is concerned, therefore, stocks, bosses, and batholiths belong to a primary division of intrusive bodies which may be defined as not demonstrably due to injection. The principle is negative, it leaves the method of intrusion unstated, but it brings into clear relief a principal contrast existing between the greatest of intrusions on the one hand, and dikes, sheets, laccoliths, etc., on the other.

The subdivision of the two classes is given in the following table, which is a somewhat altered reprint of that in the 1905 paper.

A. INJECTED MASSES.

- I. *Concordant injections* (injected along bedding planes).
  - 1. Intrusive sheets, homogeneous and differentiated.
    - a. Sills.
      - (1) Simple.
      - (2) Multiple.
      - (3) Composite.
    - b. Interformational sheets (at unconformities).
  - 2. Laccoliths, homogeneous and differentiated.
      - (1) Simple: symmetric and asymmetric.
      - (2) Multiple.
      - (3) Composite.
      - (4) Interformational (at unconformities).
  - 3. Phacoliths.
- II. *Discordant Injections*[1] (injected across bedding planes).
  - 1. Dikes, homogeneous and differentiated.
      - (1) Simple.
      - (2) Multiple.
      - (3) Composite.
  - 2. Eruptive veins: contemporaneous veins.
  - 3. Apophyses or tongues.
  - 4. Necks, homogeneous and differentiated.
  - 5. Bysmaliths.
  - 6. Chonoliths.

[1] Called "transgressive intrusions," by A. Harker, The Natural History of Igneous Rocks, New York, 1909, p. 61.

7. Ethmoliths.
8. Sphenoliths.

B. Subjacent Masses

I. *Stocks and bosses*, homogeneous and differentiated.
   (1) Simple.
   (2) Multiple.
   (3) Composite.

II. *Batholiths*, homogeneous and differentiated.
   (1) Simple.
   (2) Multiple.
   (3) Composite.

Igneous Injections

An *intrusive* **sheet** is a tabular injected body lying parallel to the bedding plane of the country rock.

In accordance with A. Geikie's definition, the standard in general usage, a **sill** is a sheet of igneous material which has been injected into a sedimentary series and has solidified there, so as to appear more or less regularly intercalated between the strata (Figs. 1, 2, and 3).[1]

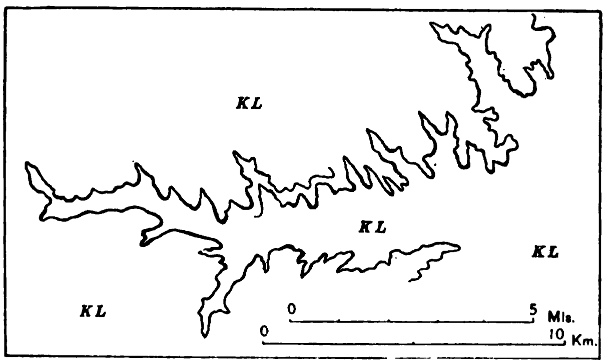


Fig. 1.—Outcrop of lamprophyric sill in flat Laramie sediments (*KL*), Colorado. (After Spanish Peaks Folio, U. S. G. S., No. 71, 1901.)

Ideally, it would be well to distinguish the class of sills which have made room for themselves by lifting flat, overlying strata, from another class which have been forced into vertical strata. The former class represents a mechanism like that of the laccoliths; the latter represents a mechanism like that of dikes as hereafter defined. But experience shows that the ideal subdivision cannot always be applied in nature and some authorities are content to use the term "sill" without directly

[1] Reprint, with originals of Figs. 2 and 3, kindly supplied by Mr. Harker.

implying the nature of the intrusive mechanism. Most of the greater recorded sills are of gabbroid or diabasic (basaltic) composition,

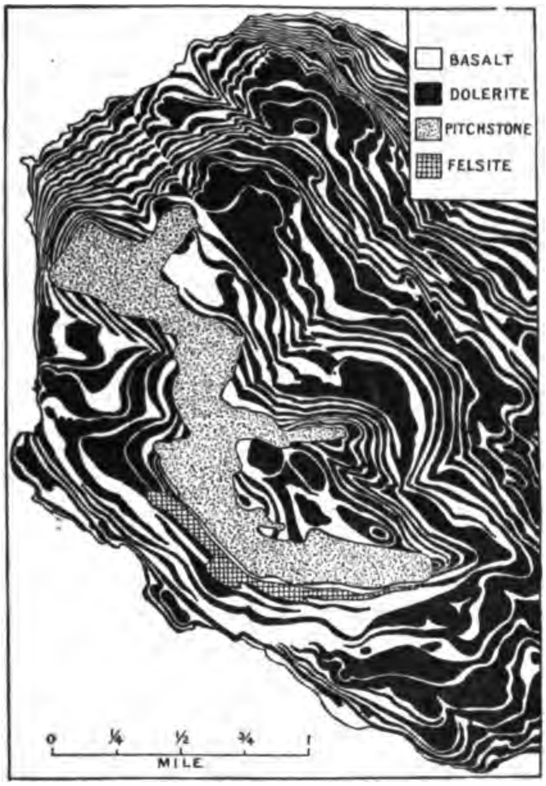


Fig. 2.—Dolerite sills cutting basalts, Isle of Eigg. (After A. Harker, Quart. Jour. Geol. Soc., Vol. 62, 1906, p. 44.)

though some of these have minor non-basaltic phases and illustrate the class of *differentiated sills*. (See Fig. 158 and pages 229 ff and 344.)

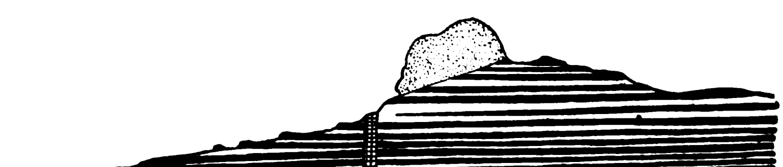


Fig. 3.—Section of area shown in Fig. 2, from S, 10° W. to N. 10° E.

A multiple sill is a compound intrusion of sill form and relations, and is the result of successive injections of one kind of magma along a bedding plane. Harker has described remarkable examples in the island of Skye; Fig. 4 is reproduced from his drawing.

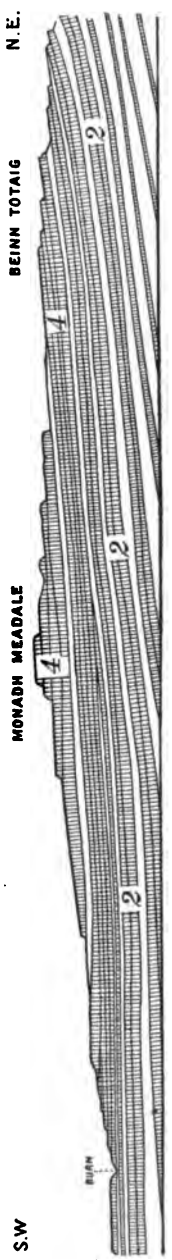


Fig. 4.—Multiple (double and quadruple) sills of dolerite (*lined*) cutting basalts (*left blank*), Island of Skye. Scale, 1:21,000. (A. Harker, Tertiary Igneous Rocks of Skye, 1904, p. 239).

A composite sill is a compound intrusion of sill form and relations, and is the result of successive injections of more than one kind of magma along a bedding plane (Fig. 5). Again Skye furnishes good examples[1] (Figs. 6 and 7). Another is figured in a recent paper on the coast geology of Greenland[2] (Fig. 200, page 447).

Sills vary in thickness from sheets of microscopic dimensions to those more than 1000 feet in thickness. In all cases it is necessary that a sill shall hold its major thickness, at least approximately, for long distances along its roof or floor; but it is obvious that there is no sharp line between sills and laccoliths.

Sills may be extremely abundant in a single outcrop. The writer has seen more than one hundred sills in a cliff section, 2500 feet high, in the pre-Cambrian sediments (Shuswap series) of the Columbia mountain range in British Columbia. He has counted twenty-five sills in a 30-foot cliff in the same terrane. The sills of the Purcell Range in the same Canadian province are as notable for their number as for great individual thicknesses.

The famous Whin sill has a maximum known thickness of but 150 feet (average thickness 80–100 feet), but its mapped outcrop is more than 80 miles in length (Fig. 29). The greatest of the Triassic sills in New Jersey reaches 1000 feet in thickness and has about 100 miles of residual length (Fig. 203). The Cape Province, South Africa, is rich in enormously extended intrusions of this class. The lowest of the dolerite sills in Calvinia is continuous over at least 3000 square miles, and one near Hopetown covers more than 5000 square miles. Another dolerite sheet between Langebergen and Tanqua valley, though reaching a maximum known thick-

[1] A. Harker, Tertiary Igneous Rocks of Skye, 1904, pp. 204 and 257.
[2] A. Heim, Meddelelser om Grönland, Vol. 47, 1911, p. 203.

ness of only 300 feet, has an outcrop more than 100 miles long. The Rooi Hoogte sheet fronts the Great Karroo for nearly 50 miles and has an outcrop more than 70 miles in length.[1]

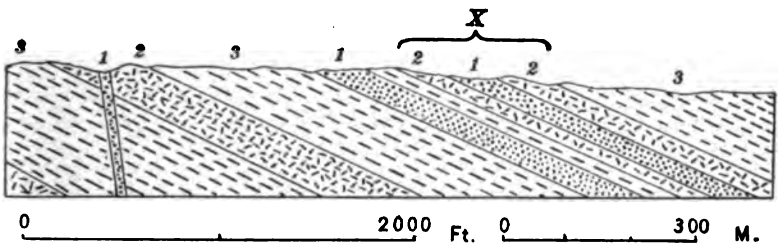


FIG. 5.—Simple and composite (*X*) sills cutting Tertiary strata at the Kettle River, British Columbia. (R. A. Daly, Memoir 38, Geol. Surv. Canada, 1912, Fig. 25.) *1*, rhomb-porphyry; *2*, pulaskite porphyry, cut by *1*; *3*, Oligocene sandstone and shale.

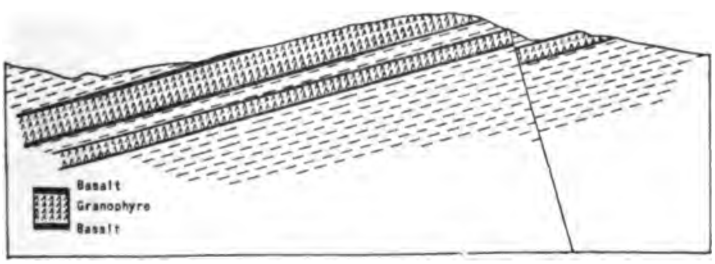


FIG. 6.—Section of a composite sill in Skye. (After A. Harker, Tertiary Igneous Rocks of Skye, 1904, p. 204.) The stratified Lias was cut by the sill of basalt; this was cut by the later sill of granophyre. The basic sill may have been double. Scale, 1:8,500.

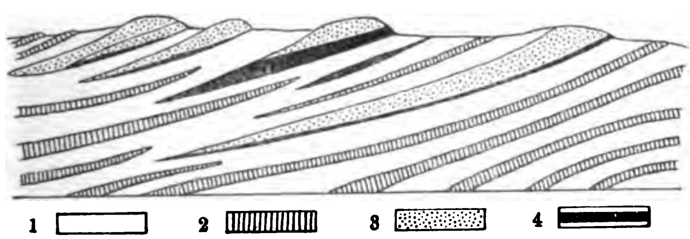


FIG. 7.—Composite laccolithic sills of Skye. (After A. Harker, Tertiary Igneous Rocks, Skye, 1904 p. 257.) *1*, basalt lavas; *2*, dolerite sills; *3*, olivine dolerite; *4*, mugearite. Scale, 1: 12,700.

Such statistics have considerable importance inasmuch as they make it easier to believe that the colossal injections of gabbro in

[1] A. W. Rogers and A. L. du Toit, Geology of Cape Colony, London, 2nd Edition, 1909, pp. 261–264; cf. same authors in Ann. Rep. Geol. Comm. Cape of Good Hope, 1903, pp. 37–39.

Minnesota (Duluth), in the Bushveldt, South Africa, etc., are laccoliths, or greatly thickened sheets, with true floors. (See Table XIV, page 230.)

Sills vary greatly in chemical composition, from peridotite to highly

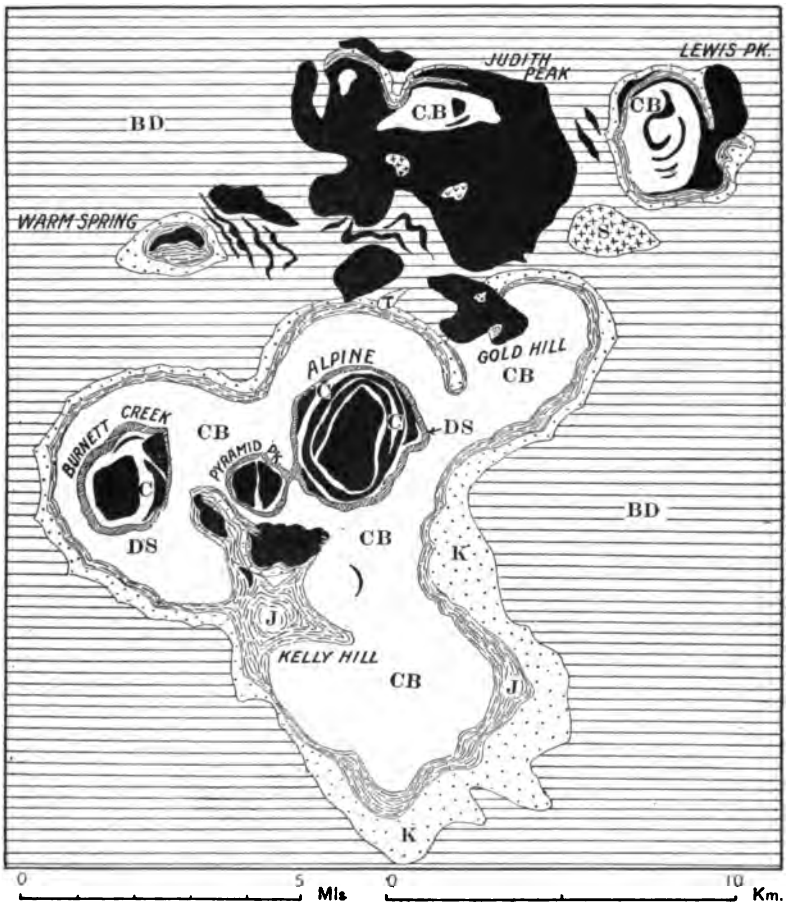


FIG. 8.—Laccoliths of the Judith Mountains, Montana. (After W. H. Weed and L. V. Pirsson, 18th Ann. Rep., U. S. G. S., Pt. 3, 1898, Plate 75.) *Solid black*, acidic porphyries of the laccoliths; *inverted carets*, granite porphyry; *S*, syenite; *T*, tinguaite; *BD*, Benton and Dakota shales and sandstones; *K*, Kootanie shales and sandstones; *J*, Jurassic shales and limestones; *CB*, Carboniferous limestone; *DS*, Devonian and Silurian limestones; *C*, Cambrian shales and limestones.

silicious aplites, but the greater, more persistent sills are in almost all cases diabasic or gabbroid (basaltic).

Closely related to sills is a tabular intrusion which has been injected along a plane of unconformity, in such fashion that the mass lies parallel to the bedding-planes of one of the invaded formations. Such bodies have been named (intrusive) *interformational sheets.* The greatest recorded example with well-determined roof and floor is that in the Sudbury District of Ontario.[1] (See Figs. 160, 161, page 347.) Like most of the great sills of the world, the magma of this Sudbury sheet has been differentiated and the process has here taken place on a scale seldom equalled in demonstrably injected bodies.

Gilbert originally described the typical **laccolith** in the following words:

"The station of the laccolite being decided, the first step in its formation is the intrusion, along a parting of strata, of a thin sheet of lava, which spreads until it has an area adequate, on the principle of the hydrostatic press, to the deformation of the covering strata. The spreading sheet always extends

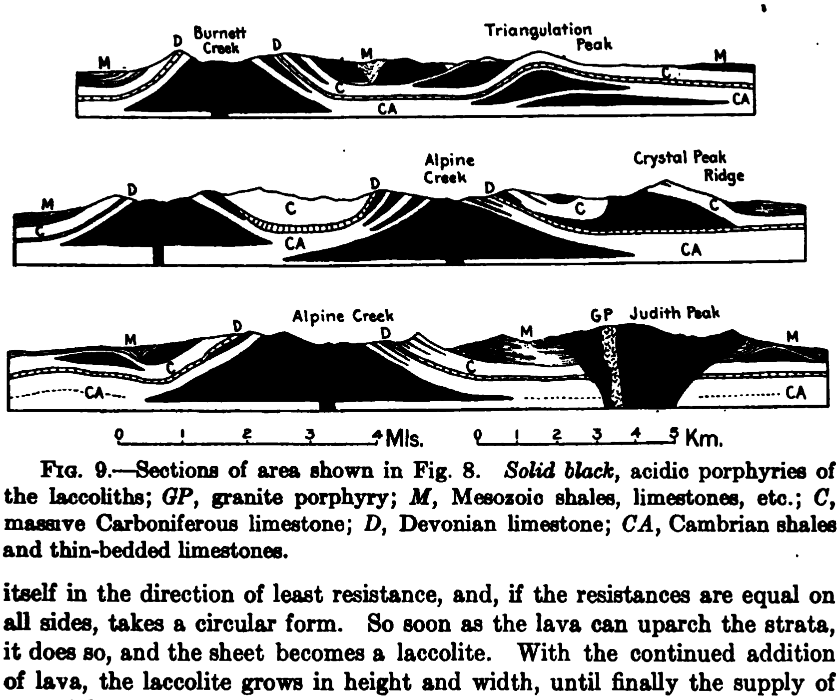


FIG. 9.—Sections of area shown in Fig. 8. *Solid black,* acidic porphyries of the laccoliths; *GP,* granite porphyry; *M,* Mesozoic shales, limestones, etc.; *C,* massive Carboniferous limestone; *D,* Devonian limestone; *CA,* Cambrian shales and thin-bedded limestones.

itself in the direction of least resistance, and, if the resistances are equal on all sides, takes a circular form. So soon as the lava can uparch the strata, it does so, and the sheet becomes a laccolite. With the continued addition of lava, the laccolite grows in height and width, until finally the supply of material or the propelling force so far diminishes that the lava clogs by congelation in its conduit and the inflow stops. . . . . .

"As a rule, laccolites are compact in form. The base, which in eleven localities was seen in section, was found flat, except where it copied the curvature of some inferior arch. Wherever the ground plan could be observed, it was found to be a short oval, the ratio of the two diameters not exceeding that of three to two. Where the profile could be observed, it was usually

[1] A. E. Barlow, Ann. Report, Geol. Survey of Canada, Vol. 14, Part H, 1904; A. P. Coleman, Report of Bureau of Mines, Ontario, Vol. 14, Part 3, 1905.

found to be a simple curve, convex upward, but in a few cases, and especially in that of the Marvine laccolite, the upper surface undulates. The height is never more than one-third of the width, but is frequently much less, and the average ratio of all the measurements I am able to combine is one to seven.

"The ground plan approximates a circle, and the type form is probably a solid of revolution—such as the half of an oblate spheroid. . . . .

"The laccolite is a greatly thickened sheet [sill] and the sheet [sill] is a broad, thin, attenuated laccolite. . . . .

"The laccolite in its formation is constantly solving a problem of 'least force' and its form is a result. . . . . A laccolite grows 'by lifting its cover.'"[1]

Those who have made actual researches among laccoliths, and have preserved Gilbert's definition, are agreed on the following characteristics: (a) Whatever the origin of the force involved, a laccolith

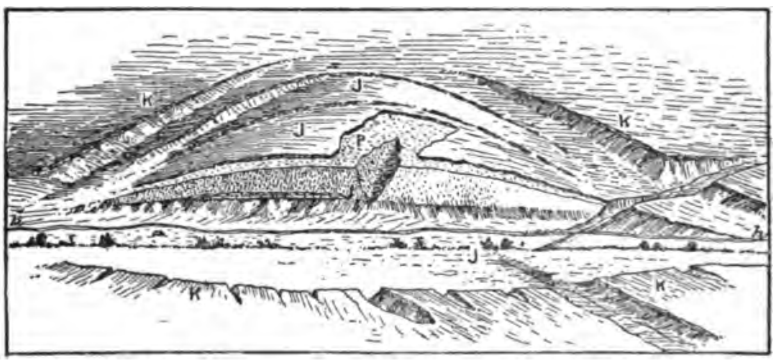


Fig. 10.—Stereographic sketch of the Warm Spring laccolith, Montana. (W. H. Weed and L. V. Pirsson, 18th Ann. Rep., U. S. G. S., Pt. 3, 1898, p. 519.) *P*, porphyry of laccolith, dotted; *K*, Cretaceous strata; *J*, Jurassic strata; *h*, road.

is always *injected*. (b) A laccolith is always in sill-relation to the invaded, stratified formation; that is, the injection has, in the main, followed a bedding-plane; but, like sills, laccoliths often locally break across the bedding. (c) A laccolith has the shape of a plano-convex or doubly convex lens flattened in the plane of bedding of the invaded formation. The lens may be symmetric or asymmetric in profile, circular, oval, or irregular in ground plan. (d) There are all transitions between sills and laccoliths.

Very large laccoliths show a feature which is not characteristic of those in the American West. The sediments underlying the Bushveldt laccolith dip inward on all sides (Fig. 162, page 351). Both

[1] G. K. Gilbert, Report on the Geology of the Henry Mountains, 1877, pp. 20, 55, 91, 95.

roof and floor of the laccolithic sheet at Sudbury have centripetal dips. Another example is found in the multiple laccolith of the Cuillin Hills, Skye.[1] The sandstones and porphyry flows in the roof of the

Fig. 11.—Section of Kelly Hill laccolith, Montana. (Same ref. as for Fig. 10, p. 499.) *Solid black*, porphyry of laccolith; *upper broken lines*, Mesozoic strata; *larger rectangles*, Carboniferous; *smaller rectangles*, Siluro-Devonian; *lower broken lines*, Cambrian.

Ilimausak "batholith," Greenland, similarly dip inward[2] (Figs. 197–9). The floors of the Duluth and Bad River laccoliths in the Lake Superior region are concave (Figs. 149, 151, and 152). These cases

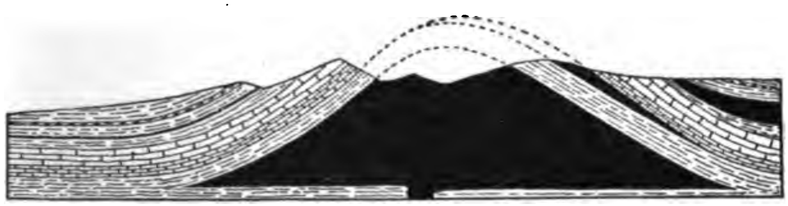


Fig. 12.—Section of Burnett Creek laccolith, Montana, showing erosion of roof more advanced than that at Kelly Hill. (Same ref. as for Fig. 10, p. 490.) Same legend as for Fig. 11.

suggest that the large-scale transfer of magma into a laccolithic chamber regularly causes subsidence of the solid rock beneath the chamber. An intrusion so deformed is best regarded as a true laccolith

Fig. 13.—Section of Warm Spring laccolith, Montana, showing erosion of roof and of laccolith more advanced than that at Burnett Creek. (Same ref. as for Fig. 10, p. 519.) *Solid black*, porphyry of laccolith; *Kd*, Dakota sandstone; *Kt*, Kootanie sandstone; *J*, Jurassic; *Kdc*, Dakota and Colorado groups.

though in form it differs systematically from the Henry Mountains type.

[1] A. Harker, Tertiary Igneous Rocks of Skye, 1904, pp. 85 and 423.

[2] N. V. Ussing, Meddelelser om Grönland, Vol. 38, 1911, p. 322.

Illustrations of *simple laccoliths* are given in Figs. 8, 9, 10, 11, 12, 13, and 14. The Tenmile District of Colorado represents laccoliths

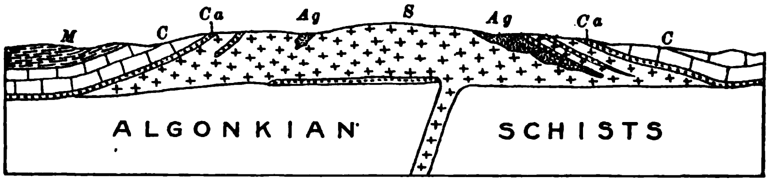


FIG. 14.—Laccolith of Bear Lodge Mts., Wyoming (interformational). (From Sundance Folio, U. S. G. S., No. 127, 1905.) *S*, syenite porphyry; *M*, Lower Mesozoic; *C*, Carboniferous; *Ca*, Cambrian; *Ag*, "Algonkian?" granite. Scale, 1:105,000.

in special abundance and, as well, examples of the transition to sills.[1]

A *multiple laccolith* may be conceived, the name being formed on

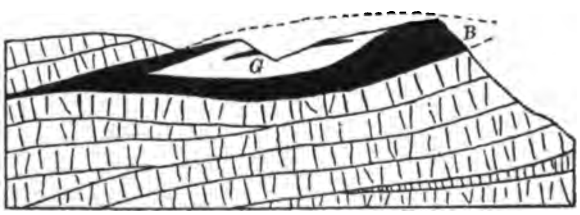


FIG. 15.—Section of composite laccolith in Skye. (After A. Harker, Tertiary Igneous Rocks of Skye, 1904, p. 209.) *B*, basalt; *G*, granophyre. The granophyre pod cuts the intrusive basalt which is itself intrusive into basaltic lavas. The maximum thickness of the laccolith is 150 ft.

the analogy of "multiple dike" and "multiple sill." It would differ from a compound laccolith only in the fact that the deformation of the

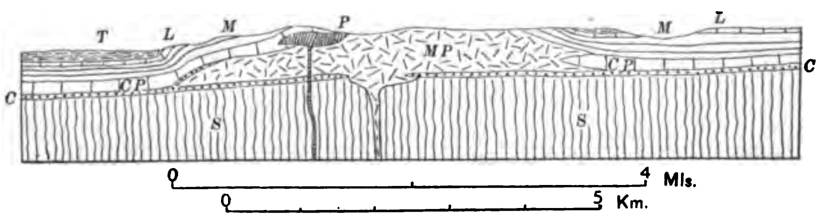


FIG. 16.—Section of composite laccolith at Black Buttes, Wyoming. (Same ref. as for Fig. 14.) *P*, Tertiary phonolite; *MP*, Tertiary monzonite porphyry; *T*, Triassic formation; *L*, Carboniferous Minnekahta limestone; *M*, Carboniferous Minnelusa sandstone; *CP*, Carboniferous Pahasapa limestone; *C*, Cambrian strata; *S*, pre-Cambrian schists.

strata, while again similar in character to that produced during the intrusion of a simple laccolith, has been due to distinctly successive

[1] Tenmile District Special Folio, U. S. Geol. Survey, No. 48, 1898.

injections of the same kind of magma. Harker describes the gabbro laccolith of the Cuillin Hills, Island of Skye, as of this origin.[1]

Composite laccoliths differ from multiple laccoliths in the respect

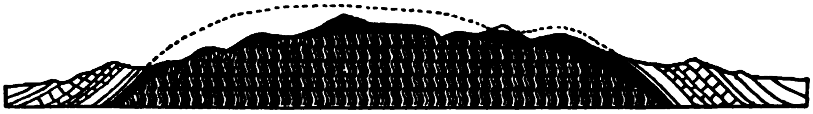


Fig. 17.—Section of interformational laccolith, Little Rocky Mts., Montana. (W. H. Weed and L. V. Pirsson, Jour. Geol., Vol. 4, 1896, p. 412.) *Solid black*, laccolith; *roof*, Paleozoic sediments; *floor*, pre-Cambrian schists. Length of section about 10 miles (16 km.).

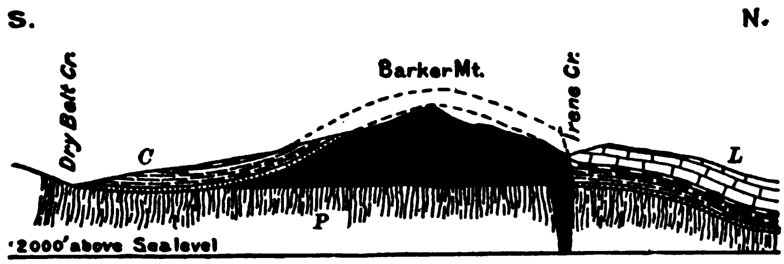


Fig. 18.—Section of asymmetric interformational laccolith at Barker Mt., Montana. (W. H. Weed, 20th Ann. Rep. U. S. G. S., Pt. 3, 1900, p. 355.) *Solid black*, porphyry of laccolith; *L*, Carboniferous limestone; *C*, Cambrian shale; *P*, pre-Cambrian. Scale, 1:97,500.

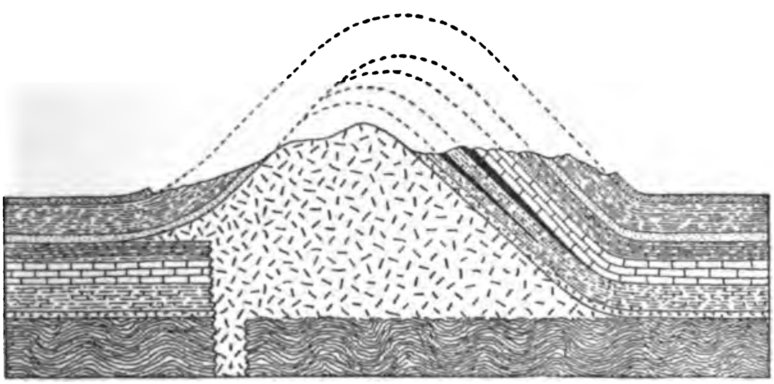


Fig. 19.—Section of asymmetric interformational laccolith at Black Butte, Montana. (Same ref. as for Fig. 10, p. 555.)

that the successive intrusions are here composed of two or more different magmas. This type is illustrated in Figs. 15 and 16.

[1] A. Harker, Tertiary Igneous Rocks of Skye, 1904, p. 88.

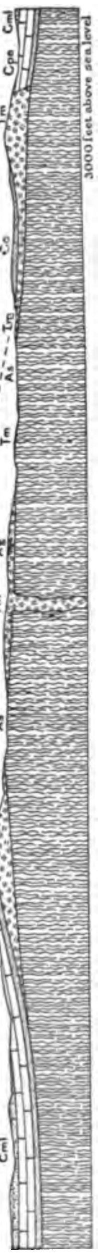


FIG. 20.—Section of Nigger Hill laccolith, Wyoming. (Same ref. as for Fig. 14.) *Tm*, monzonite and syenite porphyries; *Cml*, Minnelusa sandstone; *Cpe* Pahasapa and Englewood limestones; *Cd*, Cambrian sandstone; *Ag*, granite and pegmatite; *As*, mica schist. Horizontal and vertical scales, about 1:86,000.

In the 1905 paper a class of "compound laccoliths" was recognized and an example in the Judith Mountains of Montana has been figured and so named by Weed and Pirsson.[1] In the Judith Mountain type, as in the larger examples of laccoliths in the Henry Mountains, the whole intrusive body is divided by strong beds of the invaded formation. This gives the appearance of a number of distinct intrusions, one of them dominating, the others subsidiary, in size, but all of them composed of the same kind of material. If the magma had all been intruded at practically the same time, we have the "compound laccolith" of Weed and Pirsson. Actual practice has shown that it is difficult for students to remember the distinctions between "compound," "multiple," and "composite" laccoliths. Hence, it is here suggested that the rare bodies of the Judith Mountain type be described as "divided" simple laccoliths.

Like interformational sheets, a few bodies of laccolithic form and origin have been injected along planes of unconformity. For want of a better name these may be called "*interformational laccoliths.*" Examples have been found by Weed and Pirsson,[2] J. D. Irving,[3] and by Darton[4] (Figs. 17, 18, 19, 20).

Very seldom are the feeding channels of laccoliths exposed. Students of these bodies agree in postulating narrow channels, actually dikes or of dike-like proportions.

Laccoliths vary greatly in dimensions, the thicknesses ranging from a fraction of an inch to several miles. Gilbert has estimated that 10 cubic miles is the approximate volume of the Mt. Hillers intrusive, the largest of the classic Henry Mountain laccoliths in Utah. Its depth is about 7000 feet, and its diameters are four miles

[1] W. H. Weed and L. V. Pirsson, 18th Ann. Rep. U. S. Geol. Survey, Part 3, 1898, p. 580.

[2] W. H. Weed and L. V. Pirsson, Jour. Geology, Vol. 4, 1896, p. 402.

[3] J. D. Irving, Annals New York Acad. Sciences, Vol. 12, 1899, p. 206.

[4] N. H. Darton, Sundance Folio, No. 127, U. S. Geol. Survey, structure sections.

and three and three-quarter miles.[1] One of the largest bodies for which a probable laccolithic origin has been indicated is the Duluth gabbro of Minnesota. Van Hise and Leith are among those who favor such a mode of intrusion for this body.[2] At a minimum estimate it has an outcrop covering 2400 square miles, with a length of 125 miles, and a maximum width of about 25 miles. (See Fig. 149, page 325.) If, as assumed by Van Hise and Leith, the average dip of the intrusive body is ten degrees, its maximum thickness where exposed is about 22,000 feet. These estimates do not include the area of the "red rock," which is very closely associated with the gabbro, and may possibly be regarded as an acidic, upper phase of the laccolith. Still more imposing is the Bushveldt laccolith with its 250 miles of length and 80 miles of width (Fig. 162, page 351).

These bodies also vary greatly in chemical composition. Cross has recorded the most thorough canvass yet made of the laccoliths of Colorado, Utah, and Arizona.[3] His list of the petrographic types includes: augite porphyrite, hornblende porphyrite, porphyritic augite diorite, quartz porphyrite, and quartz porphyry. Some of these species would now, probably, be called monzonite porphyries. In the Highwood Mountains of Montana the rock types forming laccoliths include sodalite syenite, shonkinite, basic syenite, and leucite-basalt porphyry.[4] Granite porphyry, rhyolite porphyry, syenite porphyry, and diorite porphyrite compose the many laccoliths of the Judith Mountains, Montana.[5]

The types represented in the laccoliths of the Black Hills, South Dakota, include grorudite, phonolite, rhyolite porphyry, dacite, andesite porphyry, syenite porphyry, and diorite porphyrite.[6] Hills describes laccoliths of doleritic rock, found in Huerfano Park, Colorado.[7] Gabbro laccoliths are reported from the island of Skye, and they seem to have been developed on a large scale in the area covered by the Roseburg folio of the United States Geological Survey, as well as in Minnesota and other states of the union. At least ten of the laccoliths underlying the thirty-two domes of the Runn of Cutch are composed of quartz-bearing diabase.[8] An ultra-

[1] G. K. Gilbert, Report on the Geology of the Henry Mountains, Washington, 1877, p. 30.

[2] C. R. Van Hise and C. K. Leith, Monograph 52, U. S. Geol. Survey, 1911, p. 372.

[3] W. Cross, 14th Ann. Rep. U. S. Geol. Survey, Part 2, 1894, p. 165.

[4] L. V. Pirsson, Bull. 237, U. S. Geol. Survey, 1905, p. 57 ff.

[5] W. H. Weed and L. V. Pirsson, 18th Ann. Rep., U. S. Geol. Survey, Part 3, 1898, p. 557 ff.

[6] T. A. Jaggar, Jr., 21st Ann. Report, U. S. Geol. Survey, Part 3, 1901, p. 182.

[7] R. C. Hills, Proc. Colorado Scientific Society, Vol. 3, Part 2, 1889, p. 226.

[8] J. F. Blake, Quart. Jour. Geol. Soc., Vol. 54, 1898, p. 12.

femic, wehrlitic, intrusive body at Kilauea, Hawaii, has arched the overlying ash beds after the manner of a laccolith and has been so classed.[1] True granite is the most conspicuous phase of the differentiated laccolith in the Bushveldt, Transvaal. Theralite forms laccoliths in the Crazy Mountains of Montana.[2] Ijolite, urtite, and nephelite syenite compose the supposed laccolith of the Kola peninsula.

Without further multiplying examples, it is clear that all, or nearly all, the igneous clans are represented among the laccolithic injections. For some years geologists were inclined to emphasize the view that a chemical composition of intermediate (mediosilicic) character was generally an essential feature of laccolithic rock. So many instances of highly acid types as well as of strongly basic types have now been recorded that it is no longer safe to say how general the rule may be. At any rate, the relation of the peculiar mechanism of laccolithic injection to the chemical composition of the intruding magma is now too obscure to be of great use in petrogenesis.

Among the special students of laccoliths the hypothesis prevails that great viscosity is an essential prerequisite in this mechanism. If it be true, this view has an important consequence. Some of the Montana laccoliths (Square Butte, Shonkin Sag) clearly show evidences of magmatic viscosity which after injection was still low enough to permit of truly spectacular differentiation. The prevalent hypothesis, if applicable to these cases, implies that thorough-going differentiation can take place in highly viscous magma. It would seem, in fact, that the thick Square Butte intrusive is a fairly typical laccolith, and that this hypothesis should apply there, if anywhere. The Shonkin Sag body is more like a sill, suggesting a relatively low initial viscosity for its magma. The whole problem is worthy of investigation because of the light it may throw on the physical conditions for magmatic differentiation, as well as on those for laccolithic injection.

Phacoliths.—Harker has introduced the name "phacolite" (here "phacolith," meaning literally "lens-rock") for a third class of concordant injections. His description may be quoted.

"In the ideal case of a system of undulatory folds there is increased pressure and compression in the middle limbs of the folds, but in the crests and troughs a relief of pressure and a certain tendency to opening of the bedding-surfaces. A concurrent influx of molten magma will therefore find its way along the crests and troughs of the wave-like folds. Intrusive bodies corresponding more or less closely with this ideal case are common in folded districts. Since some distinctive name seems to be needed, we may call them *phacolites*. The name laccolite has often been extended to include

[1] R. A. Daly, Proc. Amer. Acad. Arts and Sciences, Vol. 47, 1911, p. 115.

[2] Personal communication from J. E. Wolff.

such bodies, but this is to confuse together two things radically different. The intrusions now considered are not, like true laccolites, the cause of the attendant folding, but rather a consequence of it. The situation, habit, magnitude, and form of the phacolite are all determined by the circumstances of the folding itself. In cross-section it has not the plano-convex shape of

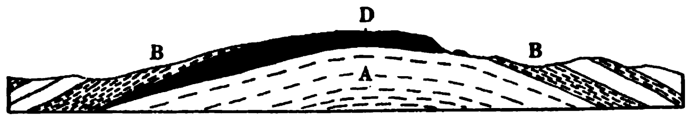


Fig. 21.—Dolerite phacolith (*D*) cutting Ordovician strata, Corndon, Shropshire. (After A. Harker, The Natural History of Igneous Rocks, 1909, p. 78.) *B*, Stapeley ash and andesite; *A*, Mytton flags and Hope shales.

the laccolite, but presents typically a meniscus, or sometimes a doubly convex form. Except where the folding has the character of a dome, a phacolite does not show the nearly circular ground-plan of a laccolite, but has a long diameter in the direction of the axes of folding. As regards the mechanical conditions of its injection, the phacolite resembles rather the small subsidiary

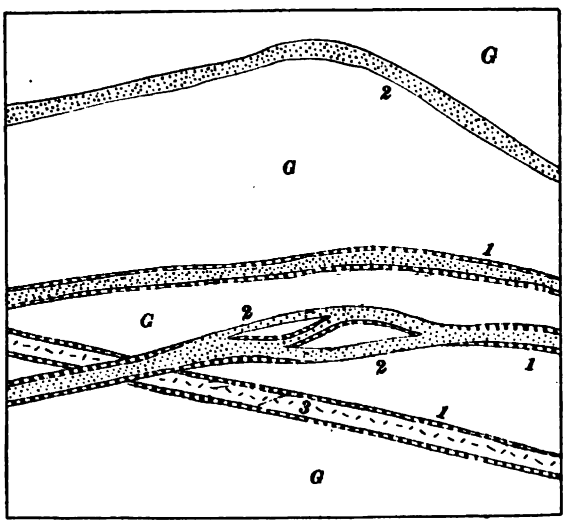


Fig. 22.—Differentiated dikes in the Trusenthal, Thuringia. (After H. Bücking, Jahrb. k. preuss. geol. Landesanst., 1887, Taf. V.) *3*, granite porphyry; *2*, syenite porphyry; *1*, melaphyre; *G*, granite. Width of dikes somewhat exaggerated. Scale, 1:5,000.

intrusions which sometimes accompany a laccolite, and are consequences of the sharp flexure caused by the primary intrusion.

"The ideal type of phacolite is subject to many modifications, in accordance with the varying mechanical conditions of intrusion. Some bodies of this nature, in the Alps and elsewhere, attain large dimensions. According to Baltzer, the Aletsch mass is 18 or 19 miles long and 2 miles broad, with a visible thickness of 2600 to 3200 feet, while the St. Gotthard mass has a length of 45 miles and a breadth of 2 or 3 miles."[1]

Fig. 21 is copied from Harker's illustration of this intrusive type.

According to what seems to be the commonest usage, a *simple* dike (a) is an injected body, (b) has nearly or quite parallel walls, (c) is

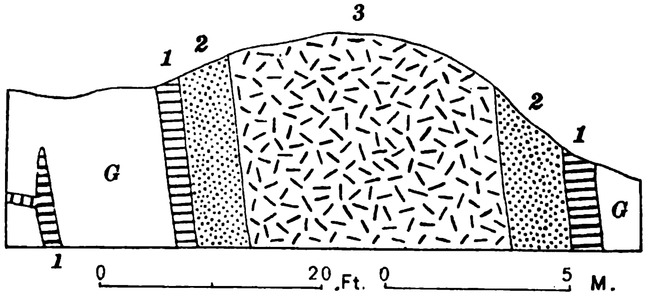


FIG. 23.—Section of differentiated dike in the Elmenthal, Thuringia. (Same legend and ref. as for Fig. 22.)

narrow in proportion to its outcropping edge, (d) cuts across the bedding when the invaded formation is stratified, and (e) has any angle of dip.

When stratification and cleavage or schistosity are not coincident such an intrusive body is generally called a dike, even though it follows the planes of cleavage or schistosity. This usage is adopted in the present classification.

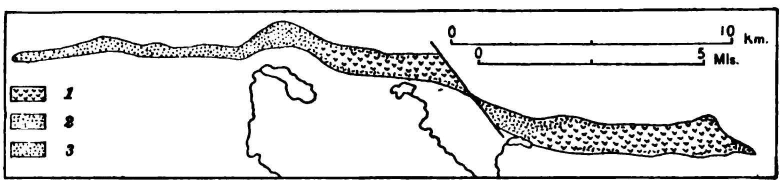


FIG. 24.—Plan of the great differentiated dike at Brefven, Sweden. (After K. Winge, Geol. Fören. Förh., Vol. 18, 1896, p. 187.) *1*, granite porphyry; *2*, intermediate rock; *3*, olivine diabase.

Some simple dikes exhibit segregation of magmatic elements after injection and may be described as *differentiated dikes* (Figs. 22, 23, and 24).

Multiple dikes are intrusions of dike form, due to successive injections of one kind of magma into the same fissure (Figs. 25 and 26).

[1] A. Harker, The Natural History of Igneous Rocks, New York, 1909, pp. 77–78.

The instances described in geological literature seem to be much more numerous than those of either multiple sills or multiple laccoliths.[1]

Composite dikes are intrusions of dike form, due to successive injections of chemically different magmas into the same fissure. This nomenclature brings out the analogy with "multiple" and "composite" sills and laccoliths—types already well named and established. Dikes of this class are illustrated in Figs. 27 and 28.

Harker has published a useful set of diagrams illustrating certain irregularities in the forms of dikes.[2]

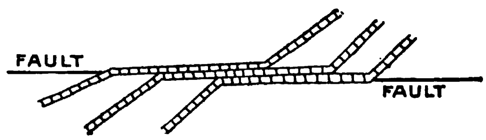


FIG. 25.—Multiple dike following fault plane in Cowal. (After W. Gunn, C. T. Clough, and J. B. Hill, Geology of Cowal, 1897, p. 144.)

No lower limit can be safely assigned to the possible width of a dike. For dikes of small length the limit is certainly less than 1 millimeter. Emerson describes a glassy (diabase) dike in Pelham, Massachusetts, only .9 millimeter wide, with apophyses respectively .5 millimeter and .02 millimeter wide. A second tachylitic dike, also cutting gneiss in the same region, is 2 millimeters wide, with apophyses about .1 millimeter wide.[3] No sharp line can be drawn between true dikes and mineral veins deposited by water or by other volatile

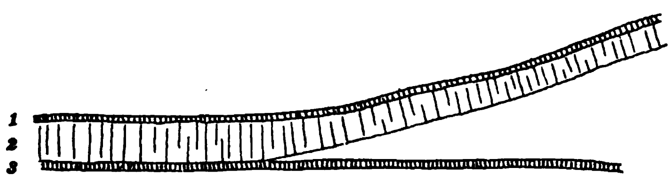


FIG. 26.—Multiple (triple) basaltic dike cutting granophyre, St. Kilda Island. (After A. Geikie, Ancient Volcanoes of Great Britain, 1897, Vol. 2, p. 417.) *1*, *2*, and *3*, separate intrusions.

fluids, which are capable of searching out the minutest crevices in rock. Yet multitudes of dikes of "dry," specially basic magma have outcrop lengths of hundreds of feet, with widths of much less than 1 foot. Such dimensions imply both low magmatic viscosity and great

[1] For good examples see: T. Thorrodsen, Petermann's Geog. Mitt., Erg. Heft, Vol. 32, 1905, p. 249; A. Geikie, Text-book of Geology, 4th ed., Vol. 2, 1903, p. 746.

[2] The Natural History of Igneous Rocks, New York, 1909, p. 74.

[3] B. K. Emerson, Monograph 29, U. S. Geol. Survey, 1898, p. 416.

rapidity of injection. In many cases the injection necessarily seems to have progressed with almost explosive violence. Barrell has ably discussed this matter, which is evidently of importance to the theory of intrusive mechanism in general.[1]

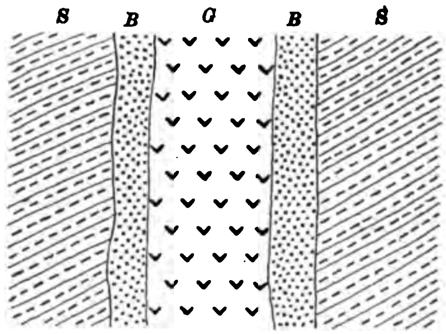


Fig. 27.—Composite dike, Broadford, Skye. (After A. Geikie, same ref. as for Fig. 26, p. 162.) *G*, granophyre; *B*, basalt, cut by *G*; *S*, Torridonian sandstone.

It is instructive to note the great lengths of outcrop determined by some of the largest known dikes. Two diabase dikes in northern Maryland are shown on the State map to have respective lengths of 38 miles and 45 miles.[2] Rogers and du Toit describe a dolerite dike

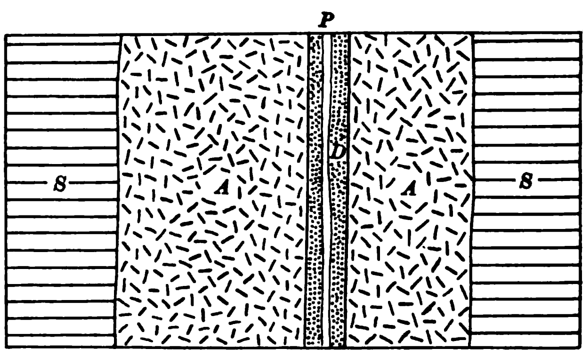


Fig. 28.—Composite dike, Tormore, Arran. (After J. W. Judd, Quart. Jour. Geol. Soc., Vol. 49, 1893, p. 556.) *P*, pitchstone (dacite); *D*, dacite (quartz felsite), cut by *P*; *A*, augite andesite, cut by *D*; *S*, sandstone. Scale, 1:300.

in Matatiele, Cape Province, which is 15 miles long and up to 1 mile in width; another, running through Beukes Fontein, is 13 miles long and

[1] J. Barrell, Prof. Paper, No. 57, U. S. Geol. Survey, 1907, pp. 157–159.

[2] Maryland Geol. Survey, Vol. 6, 1906.

about 100 feet wide.[1] A third dike, over 45 miles long, runs between Mt. Fletcher and Mt. Frere in the Drakensberg region.[2]

A. Geikie states that the Cleveland dike of northern England is at least 110 miles long and may be as much as 190 miles. Scottish dikes, respectively 25, 30, 36, 47, 50, 58, and 60 miles in length, have been recorded.[3] (See Fig. 29.) The well known Brefven dike of Sweden is over 20 miles in length and reaches a width of more than a mile[4] (Fig. 24). Thoroddsen states that some of the basaltic dikes of Iceland may reach lengths of from 30 to 65 miles. Many of them are more than 10 miles long.[5]

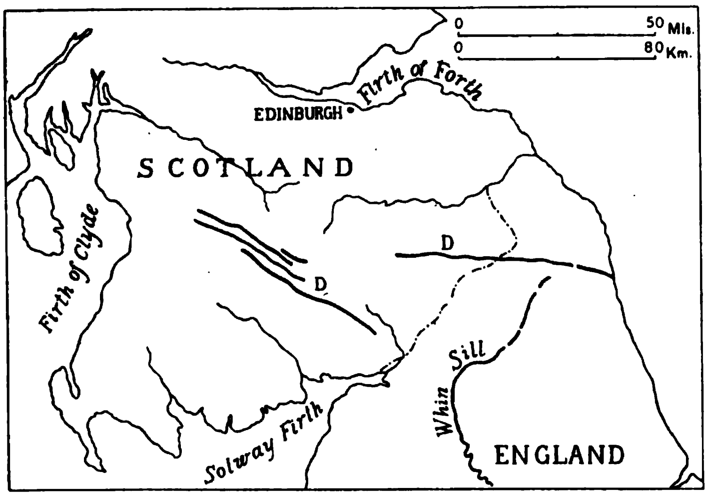


FIG. 29.—Map showing position of long dikes (*D*) and of the Whin sill. (After Government geol. map of Scotland, pub. by Stanford.)

One of the most remarkable assemblages of dikes yet mapped is that in the Spanish Peaks district of Colorado (Fig. 30; see also Figs. 70 and 165).

These examples show that the lengths of dike outcrops are of the same order of magnitude as the lengths of the greatest batholiths yet mapped. On the other hand, the width of dikes, namely, tabular, cross-cutting injections with the characteristic chilled contacts, is seldom as much as a mile. It is questionable that the width of any mapped dike is as much as 3 miles. The average width of mapped

[1] A. W. Rogers and A. L. du Toit, Geology of Cape Colony, 2nd ed., London, 1909, pp. 231 and 260.

[2] A. L. du Toit, 15th Ann. Rep. Geol. Comm. Cape of Good Hope, 1910, p. 99.

[3] A. Geikie, Ancient Volcanoes of Great Britain, London, Vol. 2, 1897, p. 143.

[4] P. J. Holmquist, Bull. Geol. Inst. Upsala, Vol. 7, 1906, p. 107.

[5] T. Thoroddsen, Petermann's Mitt., Erg. Heft No. 152, 1905, pp. 250–251.

dikes is probably well under 100 feet, if, indeed, it is not less than 40 feet.

A *dike system* is a local group of roughly parallel dikes injected in the same intrusive epoch. As a rule these follow master joints in the country rock. Such systems can sometimes be seen, after sufficient erosion, to have been the feeders of major fissure eruptions. (See Figs. 31 and 70, page 121.)

It is not necessary to repeat the statement included in Chapter II,

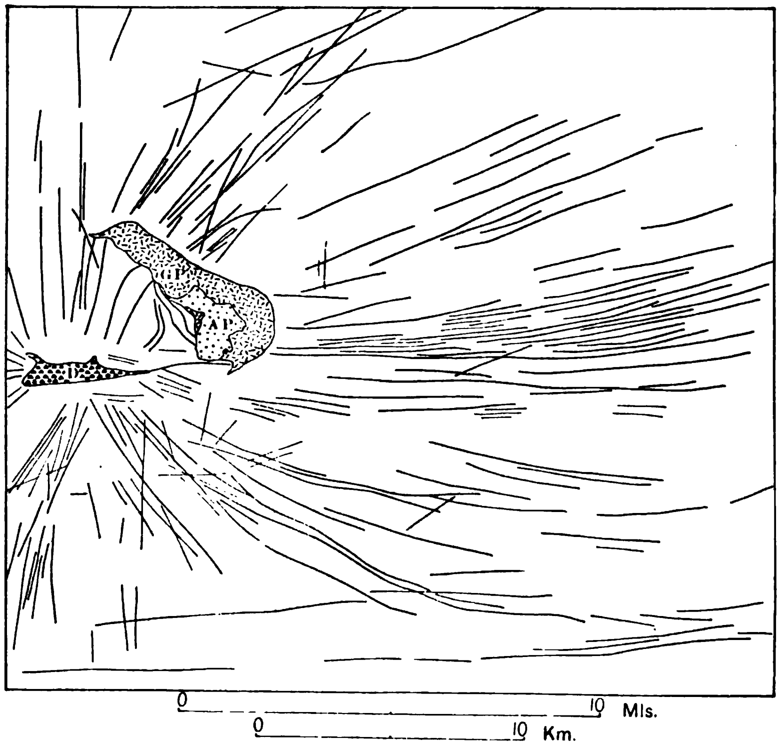


FIG. 30.—Map of dike system, apophysal from stocks, Colorado. (Spanish Peaks Folio, No. 71, U. S. G. S., 1901.) *GP*, granite porphyry; *AP*, augite-granite porphyry; *D*, augite diorite.

as to the chemical range manifested in the dike rocks. All the great clans are represented in the aschistic class, which are often simply physical satellites of batholiths or stocks. The diaschistic dikes are clearly modified offshoots of the magma in larger magma chambers and may be described as chemical satellites of these.

Intrusive veins were long ago defined by Jukes in the following words: "When the injected mass has arisen along an opened fissure, and solidified there as a wall-like intrusion, it is called a *dyke*. When its path has been less regularly defined, and penetrates the surrounding rocks in a wavy thread-like fashion, this irregular protrusion is called a *vein*."[1]

As suggested to the writer by Mr. R. W. Brock, Director of the Geological Survey of Canada, there would be distinct advantage if the term "vein" were restricted as much as possible to the tabular bodies formed by deposition from solutions with a high proportion of volatile matter. Such definition seems advisable even in spite of the difficulty of distinguishing veins from some kinds of dikes.

According to A. Geikie's definition, a *contemporaneous vein* "forms part of the igneous rock in which it occurs, but belongs to a later

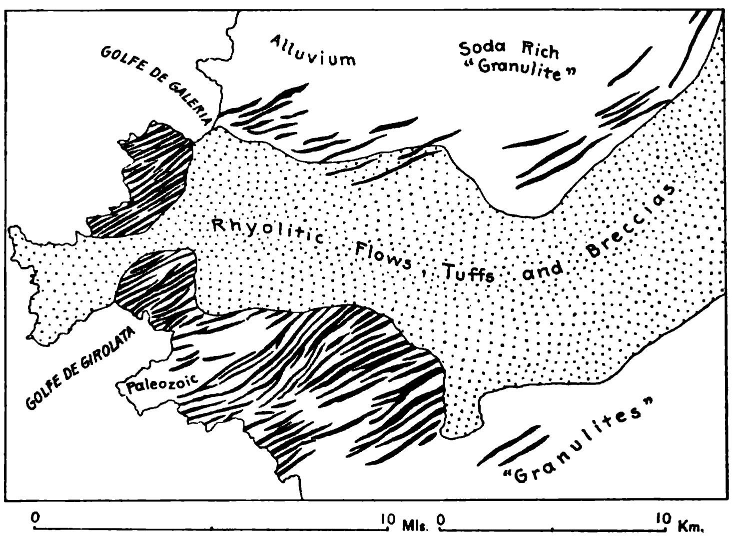


FIG. 31.—Dike system composed of rhyolite (*solid black*) in Corsica. (After J. Deprat, Bull. serv. carte géol. France, t. 17, 1907, Pl. I.)

period of consolidation than the portion into which it has been injected."[2]

Apophyses or tongues are dikes or veins which, either directly or by inference from field relations, can be traced to larger intrusive bodies as the source of magmatic supply of dike or vein.

Volcanic Neck.—The solid lava in a volcanic vent must be considered as intrusive into the wall rock, where this is non-volcanic, or is composed of older lava or pyroclastic material like tuff or agglomerate. Discussion and illustration of necks will, however, be postponed to Chapter VII, which deals with the forms of volcanic bodies.

[1] J. B. Jukes, Manual of Geology, edited by A. Geikie, 1872, p. 263.

[2] A. Geikie, Text-book of Geology, 4th ed., London, 1903, p. 738.

Bysmaliths.—Iddings has described a "bysmalith" as an injected body filling a "more or less circular cone or cylinder of strata, having the form of a plug, which might be driven out at the surface of the earth, or might terminate in a dome of strata resembling the dome over a laccolith." The downward termination of the original type bysmalith (Mt. Holmes) is found in a hypothetical Archean floor on which the porphyry of the bysmalith rests. This body is sectioned in Plate 5 of Monograph 32, Part 2, of the U. S. Geol. Survey (1899). No other bysmaliths appear to have been described under that name.

Chonoliths.—There remains for distinction a class of injected igneous bodies which are not included in any of the above-mentioned categories. In the dislocation of rock formations such as is brought about during mountain-building, actual or potential cavities are formed within the earth's crust. These are occasionally filled with igneous magma squeezed into the individual cavity from below, from the side, or, it may be, from above. Dikes, sills, and bodies of laccolithic form (though not strictly of the laccolithic mode of intrusion, as designated by Gilbert) may thus originate. Yet very often the shape of the intruded mass is so irregular, and its relations to the invaded formations so complicated, that the body cannot be classified in any of the divisions so far named. Again, irregular injected bodies of a similarly indefinite variety of form are due to the active crowding-aside and mashing of the country rock which is forced asunder by the magma under pressure. Or, thirdly, such bodies may be due to a combination of the two primary causes—orogenic stress opening cavities, and hydrostatic or other pressure emanating from the magma itself and widening the cavities.

The number and total volume of these irregular intrusions possibly rival the number and volume of all the true laccoliths of the world. In the average mountain range the geologist is more likely to encounter injected bodies of the former kind than he is to discover true laccoliths.

No generally accepted name has yet been proposed for such irregular intrusions. "Laccolith" cannot be used, since that term denotes a definite form, and also implies a special mode of intrusion different from that here conceived. The writer has not been able to find a simple English word for the purpose, and suggests a name formed from the Greek on the analogy of "laccolith," "bysmalith," and "batholith." It is "chonolith," derived from χῶνος, a mold used in the casting of metal, and λίθος, a stone. The magma of a "chonolith" fills its chamber after the manner of a metal casting filling the mold. Like a casting, the "chonolith" may have any shape.

The writer is not entirely satisfied with this invention. Etymologically it errs in being too broad, since laccoliths, sills, and dikes are bodies molded against their wall-rocks. This objection is, however, more or less formal and is not so important as the objection that the chonoliths as defined include masses formed under two highly

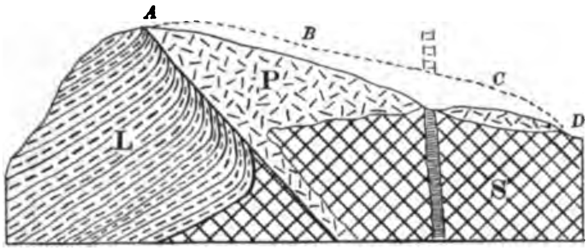


FIG. 32.—Section of chonolith (*P*), near Glen Coe, Scotland. (After drawing by Clough, Maufe, and Bailey, Quart. Jour. Geol. Soc., Vol. 65, 1909, p. 659.) *P*, intrusive porphyrite; *L*, lavas with conglomerate at base; *S*, schists; felsite dike shown; *ABCD*, hypothetical top of porphyrite intrusion. Scale, 1:19,000.

contrasted conditions. In the one case the magma is active, as in a laccolith; in the other it is largely or wholly passive during intrusion. However, the general impossibility of distinguishing the two cases in nature renders a "Sackname" useful to the field geologist. It is,

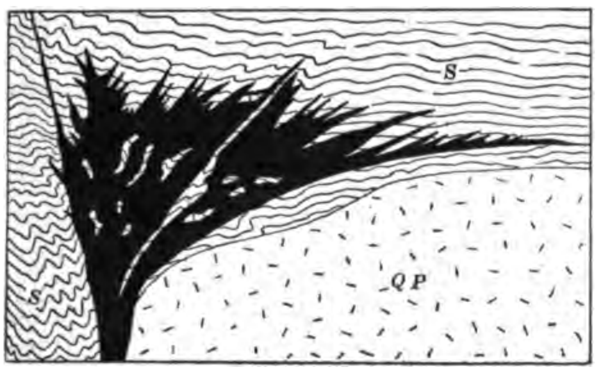


FIG. 33.—Section (hypothetical) of chonolith at Monzoni, Tyrol. (After Mrs. Ogilvie Gordon, Trans. Edin. Geol. Soc., Vol. 8, 1903, pp. 141, 175.) *Solid black*, Monzoni intrusion; *QP*, quartz porphyry; *S*, stratified rocks. Scale nearly 1:40,000.

of course, not intended that the use of this term shall discourage the further invention of good descriptive names for injected bodies, like "dike," "laccolith," "sill," etc. So far as such new classes become recognized and named, the range of the chonolithic class, as covering all the irregularly shaped injected bodies, will be restricted. If the day ever comes when the essential mechanism of each injection becomes understood, the chonolithic bodies will merit more significant names in systematic classification. Meanwhile, in spite of its shortcomings, the blanket name, "chonolith," can serve a useful purpose. As above noted, for example, it can be employed in many cases where bodies have been described as "laccoliths," though these masses have

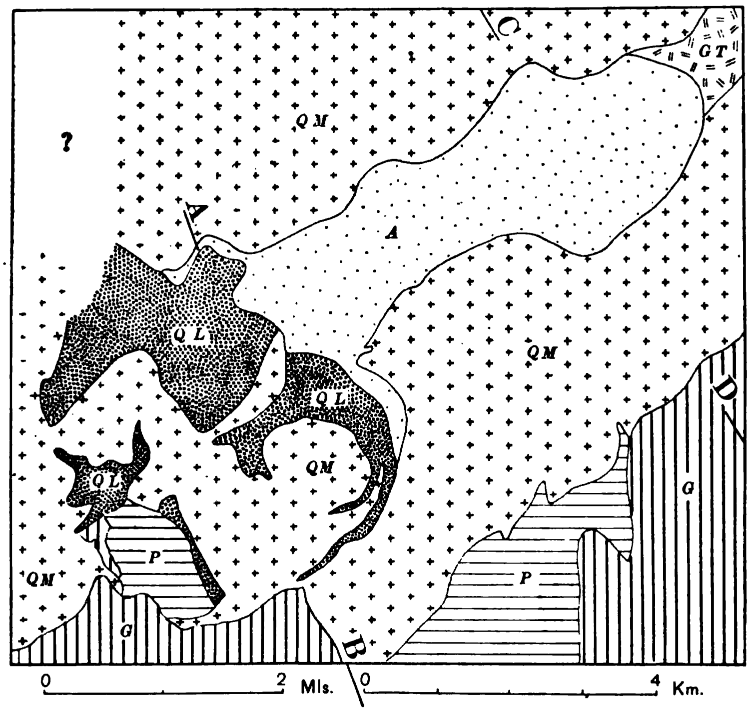


FIG. 34.—Plan of chonoliths of quartz latite porphyry (*QL*) and andesite (*A*) cutting quartz monzonite and quartz monzonite porphyry (*QM*), post-Carboniferous granite (*GT*), Paleozoic sediments (*P*), and pre-Cambrian granite (*G*); Monarch and Tomichi districts, Colorado. (After R. D. Crawford, Bull. 4, Colorado State Geol. Surv., 1913, Plate 2.) The chonoliths are probably of Tertiary age.

neither the forms nor demonstrably the mode of intrusion of true laccoliths. Such overloading of Gilbert's term must tend to injure it for scientific purposes. In a negative way the somewhat negatively defined word "chonolith" has distinct value; in this book it will have the positive value of making possible a brief form of reference to some of the world's injected masses.

A "chonolith" may be thus defined: an igneous body (a) injected into dislocated rock of any kind, stratified or not; (b) of shape and relations irregular in the sense that they are not those of a true dike, vein, sheet, laccolith, bysmalith, or neck; and (c) composed of magma passively squeezed into a subterranean orogenic chamber or actively forcing apart the country rocks.

The chamber of a chonolith may be enlarged to a subordinate degree by contact fusion on the walls, or by magmatic "stoping."

The writer's preliminary paper (1905) on this subject contains reference to many bodies which seem to belong to the chonolithic class. The cases there cited were discussed simply from the maps, sections, and reports of government geologists, working in Montana, Washington State, Colorado, and South Dakota. Other instances

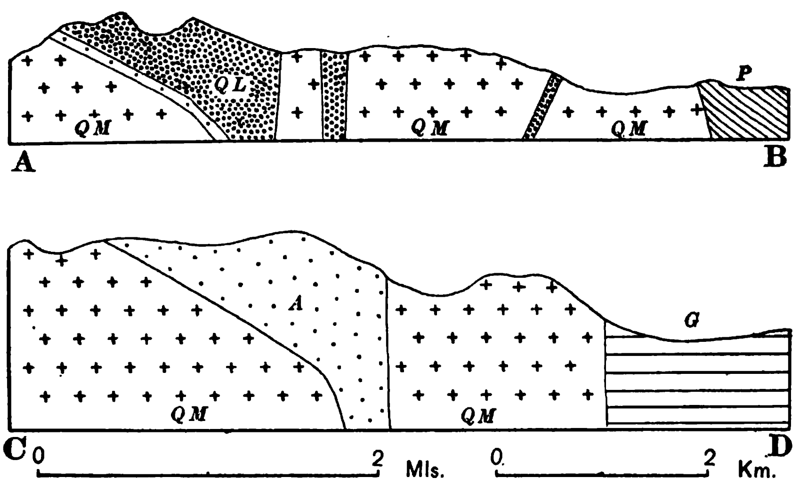


FIG. 35.—Sections along the lines A–B and C–D in Fig. 34. Underground contacts partly determined by mining.

are illustrated in Figs. 32 and 33. Still others have been described as occurring in British Columbia, Pennsylvania,[1] Colorado[2] (Figs. 34 and 35), and New South Wales.[3]

Ethmolith.—Salomon has interpreted the tonalite of the Adamello group as an injected, partially cross-cutting body. The described structural relations and mode of intrusion are those of the chonoliths, yet the form of the whole body as deduced from its outcrop is, in Salomon's opinion, definite enough to warrant a distinct name. He has accordingly called this body an "ethmolith" (literally funnel-rock).

[1] F. Bascom, Bull. 360, U. S. Geol. Survey, 1909, p. 663.

[2] R. D. Crawford, Bull. 4, Colorado Geol. Survey, 1913, p. 107.

[3] E. C. Andrews, Records Geol. Survey of New South Wales, Vol. 8, Pt. 3, 1907, (reprint) p. 13.

It is defined as a plutonic mass which narrows downwardly and is so situated that the younger beds of the (sedimentary) country-rock are bent down into contact with the igneous body.[1] Fig. 36 will convey this author's meaning better than a lengthened text description. No other masses seem to have been described under this name.

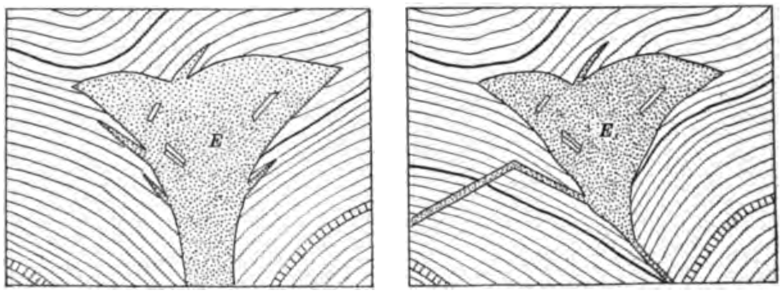


FIG. 36.—Diagrammatic section illustrating an ethmolith (*E*), with alternative suggestions as to the nature of its feeding channel. (Mte. Adamello; after W. Salomon, Sitzungsber. k. preuss. Akad. Wiss., Vol. 14, 1903, p. 310.) Stratification of invaded sediments shown by lines.

Sphenolith.—This term was invented by Burckhardt to distinguish the special form and relations of the dacitic intrusion at Las Parroquias, Mexico.[2] This body is clearly of the injected class. It is partly concordant, like a thick sill, and partly discordant. The country rocks have been displaced even to overturning and some of the movement is to be credited to pressure from the magma itself.

[1] W. Salomon, Sitzungsber. k. preuss. Akad. Wiss., phys-math. Classe, Vol. 14, 1903, p. 310.

[2] C. Burckhardt, Guide, Cong. Géol. Internat. Mexico, 1906, Part 26, p. 33.

CHAPTER VI

SUBJACENT BODIES

Definitions.—Incomparable as they are in individual volume, the subjacent masses are the least understood of all the intrusive bodies. If they were truly understood there would be no "problem" of the igneous rocks. The failure of accurate knowledge is, of course, natural. Direct observation on a batholith and direct inference as to magmatic processes within its chamber are alike dependent on unroofing. In many cases erosion has bitten thousands of feet into batholithic rock but seldom, if ever, tens of thousands of feet. In most cases each plutonic mass is fairly homogeneous throughout its known depth, which may be more than 6500 feet.[1] There is, thus, no indication that, if in any instance erosion could have penetrated to twice the depth actually attained, the batholithic mass would change its lithological character in marked degree. In brief, the geologist has access only to the upper part of batholith or stock. For several reasons which will gradually appear in the sequel, that fact is of primary importance. Properly appreciated, it will greatly aid in reaching a sound explanation of the physical and chemical changes which have occurred in the most voluminous masses. This book is, perforce, chiefly occupied with intrusives of the batholithic class. The present chapter attempts to state and illustrate merely the leading structural and related features as set forth by field geologists.

"*Batholith,*" the designation for the larger subjacent bodies, was introduced by the elder Suess at a time when his own conception of their origin was undergoing noteworthy changes. His final definition of the term is here given in free translation: "A batholith is a stock-shaped or shield-shaped mass intruded as the result of the fusion of older formations (orig. *Durchschmelzungsmasse*). On the removal of its rock-cover, and on continued denudation, the mass either holds its diameter or grows broader to unknown depths (orig. *bis in die ewige Teufe*)."[2] This definition has a strongly subjective element, as it is based on a theory of intrusion which is still in active discussion.

[1] Cf. R. A. Daly, Bull. Geol. Soc. America, Vol. 17, 1906, p. 372.

[2] E. Suess, Sitzungsberichte der K. K. Akad. der Wissenschaften, Vol. 104, 1895, p. 52.

Many authors, without implying adhesion to that or any other theory, have since used the name to denote the great bodies otherwise referred to as "central granites," "intrusive mountain-cores," "Fussgranit," etc. For present purposes it seems best to adopt the same negative position and emphasize in the definition only those features which are nearly or quite independent of petrogenic theory. On account of the supreme significance of these facts concerning subjacent bodies, they will be illustrated in some detail.

At the outset, it should be observed that all the essential characteristics of batholiths, except size, are also represented in those bodies which have long been called "*stocks*" or "*bosses*." The terms are often used synonymously. According to its general meaning, "boss" should, apparently, refer only to such stocks as are of nearly circular ground-plan at the surface of exposure. A boss is, thus, a variety of the class of stocks. Stocks themselves are simply small batholiths. The limit between these two classes cannot be other than arbitrary. In the 1905 paper the writer proposed that the upper limit of size for stocks be placed at 200 square kilometers. This figure was chosen so as to include bodies approaching those dimensions and named as stocks by certain authors. The observation of actual usage among writers during the last seven years has suggested that the limit set in the preliminary paper is too high. It is more in accord with general usage to confine the term "batholith" to those subjacent masses which, at the outcrop, cover more than 100 square kilometers or about 40 square miles; a stock is of smaller outcrop area.

Since batholiths, stocks, and bosses are similar in field relations, the description of those relations will be chiefly phrased in terms of the batholiths alone, thus avoiding useless repetition. A batholith has the following characteristics:

1. Location in orogenic belts.
2. Generally, elongation parallel to the tectonic axis of the mountain range.
3. A date of intrusion which follows, more or less closely, an antecedent period of mountain-building.
4. Cross-cutting relations.
5. An irregularly domical roof.
6. Steeply inclined walls.
7. Relative smoothness of walls.
8. Downward enlargement; no floor visible.
9. The appearance of having replaced the invaded formation during its intrusion.
10. Composition usually granitic.

General Characteristics

Location in Zones of Mountain-building.—Without known exception, the post-Cambrian subjacent bodies are all located in orogenic belts. This is not due merely to the greater depth of erosion and consequently more perfect exhibition of deep-seated formations in the

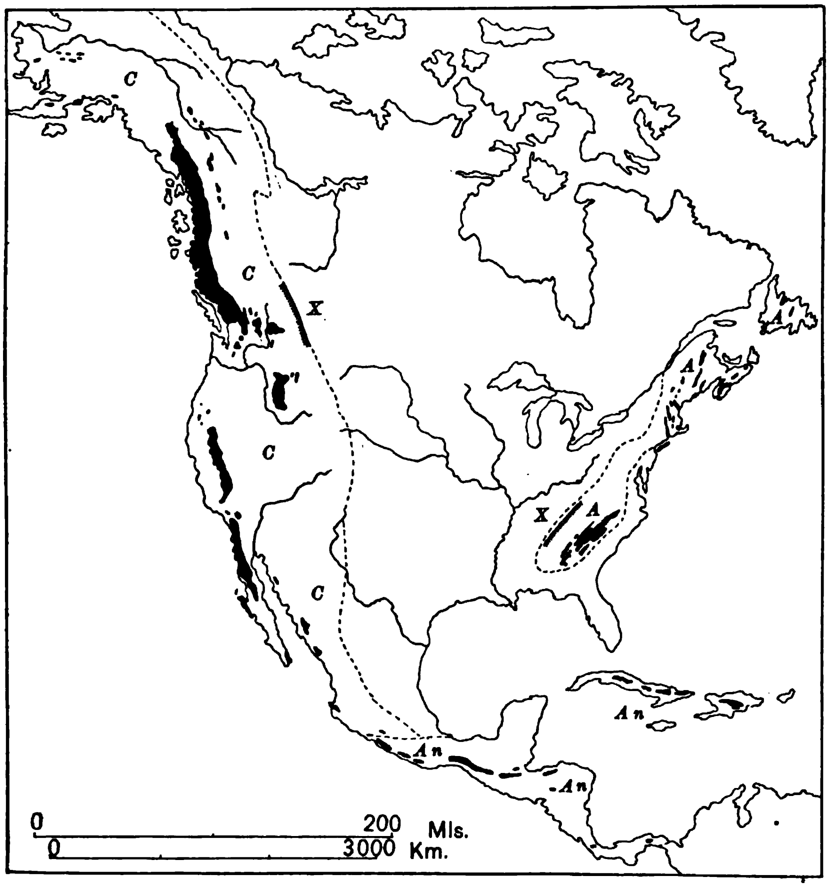


Fig. 37.—Map showing distribution of batholiths (*solid black*) in the North American Cordilleran (*C*), Appalachian (*A*), and Antillean (*An*) mountain systems. Large-scale overthrusting is demonstrated for zones marked with hachures and the symbol *X*.

mountainous regions. The denudation of some high areas characterized by the plateau type of structure has been very profound, but in no one of them has a post-Cambrian batholith cutting the flat-lying sedimentaries yet been discovered.

In a given mountain chain, the abundance and observed sizes of batholiths are in direct proportion to the intensity of the orogenic crumpling. These rules are illustrated in the North America Cordillera (Fig. 37). The largest and most numerous subjacent bodies occur in the western half of this belt, from Southern California to Bering Sea, where, on the average, the deformation of the invaded formations is much more advanced than in the eastern half of the huge belt. Similarly, the compressed folds of New England are penetrated by numerous post-Cambrian batholiths and stocks, while no subjacent

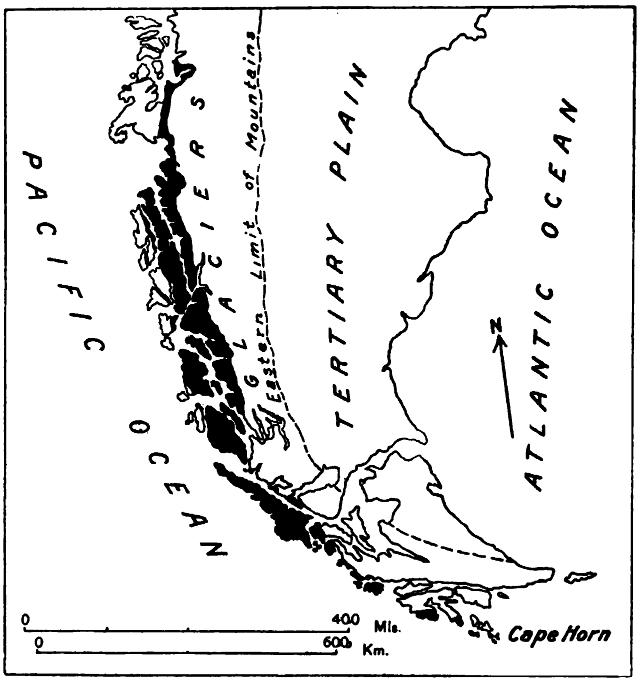


FIG. 38.—Map showing position of the great Patagonian batholith (*solid black*). (After P. D. Quensel, Bull. Geol. Inst. Univ. Upsala, Vol. 11, 1911.) Mapping approximate.

body is known to cut the equally ancient Paleozoic strata in the open folds of Pennsylvania.

The same rules apply also to the pre-Cambrian batholiths. The North American Laurentian granites and orthogneisses always cut sediments or other supra-crustal rocks whose degree of deformation constitutes a now famous major difficulty in structural and historical geology. The younger Huronian sediments, less deformed, are also less affected by batholithic intrusions. In Fennoscandia the crumpled pre-Kalevian sediments and volcanics are cut by the largest batho-

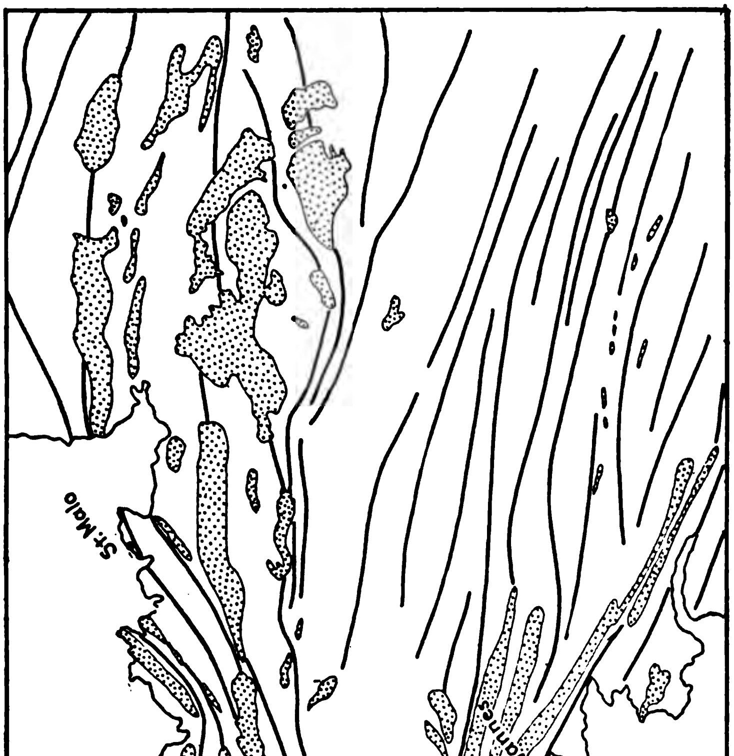


FIG. 39.—Map showing distribution of stocks and batholiths (*dotted*) in Brittany; orogenic axes shown by heavy lines.

liths of that region; while the Kalevian, Jatulian, and Jotnian sediments, successively younger and less deformed, are successively less interrupted by subjacent masses.

For the same mountain belt one may often observe that batholithic intrusion has varied in amount according to the intensity of orogenic crumpling at different geological epochs. For example, no intrusion of this kind has yet been connected with the moderate post-Pennsylvanian deformation of the coastal half of the North American Cordillera; while such intrusion, on an unrivalled scale, followed the late Jurassic orogenic revolution in this same belt.

On the other hand, zones of intense crustal deformation by no means always include visible batholiths. Granitic rocks are relatively subordinate in the outcrops of the European Alps, the Carpathians, the Caucasus, the Himalayas, and the New Zealand Alps, as in the Allegheny zone of close folding and overthrusting. In part, the explanation of this fact may be found in the local failure of sufficient unroofing by erosion, but it is quite possible that, in some of these cases, large-scale intrusion has never affected the actual mountain ranges. Perhaps the absence or subordinate development of batholiths in the Alps, the Carpathians, the Canadian Rockies, etc., may be connected with the fact that each of these ranges exhibits strong overthrusting as an essential structural feature. (See Chapter IX, page 190.)

Since mountain-systems are, in general, due to the crumpling of geosynclinal sediments, it follows that batholithic intrusions are usually situated in belts where such sedimentary prisms have been developed. The theoretical significance of this fact will be suggested in Chapter IX. It should be noted, however, that the rule does not seem to apply to most of the older pre-Cambrian batholiths, doubtless the most extensive of all in the earth. The roof rocks of the oldest batholiths of Finland, like those of the Laurentian batholiths in Canada, now include few sediments, and it is very unlikely that, in either case, the failure of sections showing truly geosynclinal thicknesses is to be explained by batholithic replacement or by deep erosion or by both processes together.

In other words, the conditions leading to the intrusion of these huge masses into the upper part of the earth's crust have changed notably between early pre-Cambrian time and post-Cambrian time; and one of the new, indispensable conditions seems to have been the antecedent development of thick geosynclinal prisms.

Elongation Parallel to Tectonic Axes.—Where erosion has stripped off much of the cover, the longer axis of a visible batholithic mass is, very generally, nearly or quite parallel to the tectonic axis of the mountain-built zone in which the mass is situated. This typical relation is, of course, likely to be more or less concealed where the removal of the cover has only begun; in such cases the exposure of the batholith is due to the accidents of denudation, and the shape of the intrusive has no necessary relation to the ground-plan of its outcrop.

Examples of parallelism between batholithic axes and tectonic

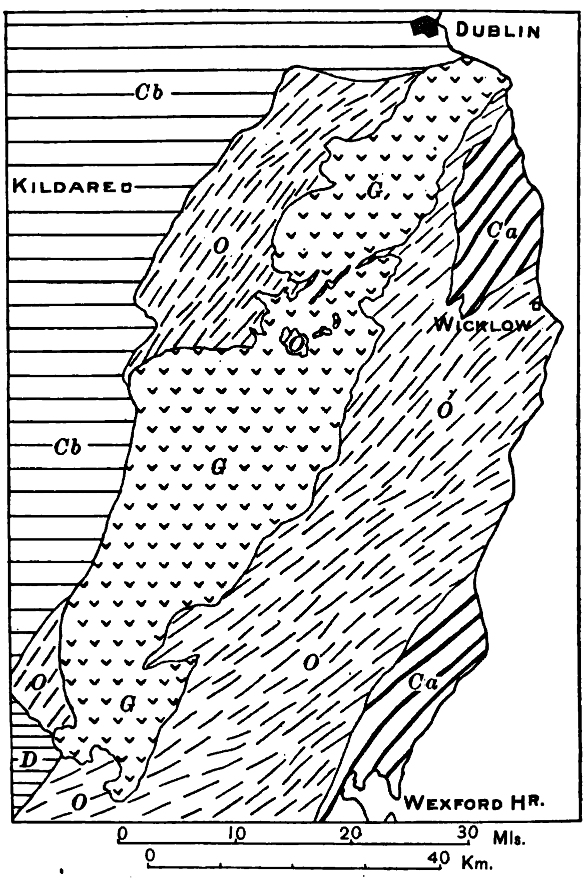


FIG. 40.—Map showing elongation of an Irish batholith (*G*) parallel to orogenic axes diagrammatically shown in the invaded Ordovician (*O*), and Cambrian (*Ca*) strata; *Cb*, Carboniferous, and *D*, Devonian.

axes in the country rock are to be found in great abundance. It will suffice to illustrate the rule by reference to standard cases in the North American Cordillera (Fig. 37); the South American Cordillera (Fig. 38); the Hercynian Mountains of Brittany (Fig. 39), Ireland (Fig. 40), and England (Fig. 41); the Pyrenees (Fig. 42); the Ural Mountains;

the Himalayas; the Atlas Mountains; the mountains of New South Wales and of New Zealand.

Those examples are all taken from areas of post-Cambrian intrusion. The pre-Cambrian batholiths have very often developed "peripheral schistosity" in their respective country rock terranes. Thereby it may become difficult to determine the relation of a batholithic axis to the average strike of the invaded formations. Exceptionally, these pre-Cambrian intrusive masses are arranged parallel or *en axe*, so as to suggest that, in these cases, they were intruded under conditions much

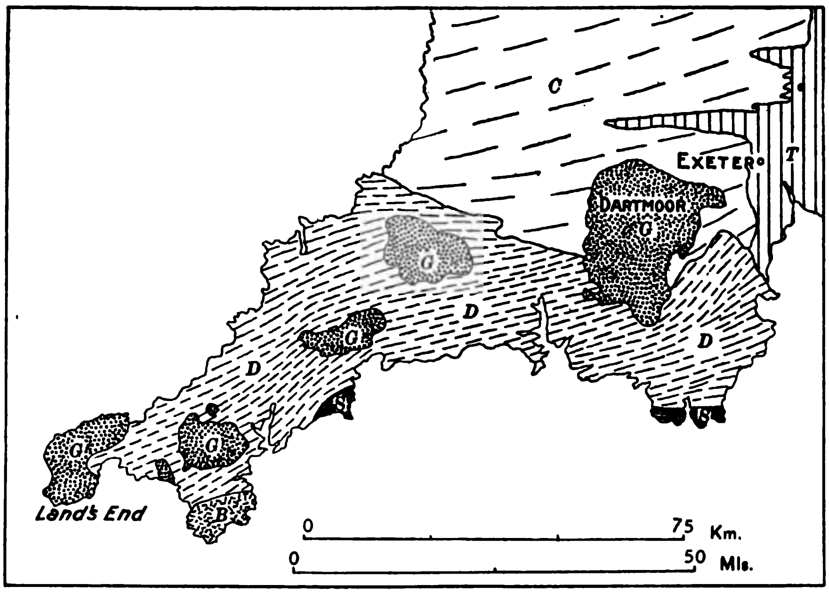


FIG. 41.—Map showing alignment of granite batholiths and stocks (*G*) in Cornwall and Devon, to orogenic axes which are shown diagrammatically. *T*, Triassic; *C*, Carboniferous; *D*, Devonian, Ordovician, and Cambrian (?); *S*, Ordovician (Lower Silurian), *B*, serpentine, etc. Map generalized.

like those of post-Cambrian batholiths. Such relations are illustrated in Ontario and in Sweden, where the invaded sediments are locally of very great thickness.

Time Relation to Mountain Building.—Without known exception, each batholithic invasion has followed more or less closely a period of strong crustal deformation affecting the older formations of the same region. This rule, which seems really to have attained the dignity of a law, is generally recognized by geologists, but no one has hitherto published a statement showing how full is the evidence. Space cannot be taken for details. The following table (VI) will

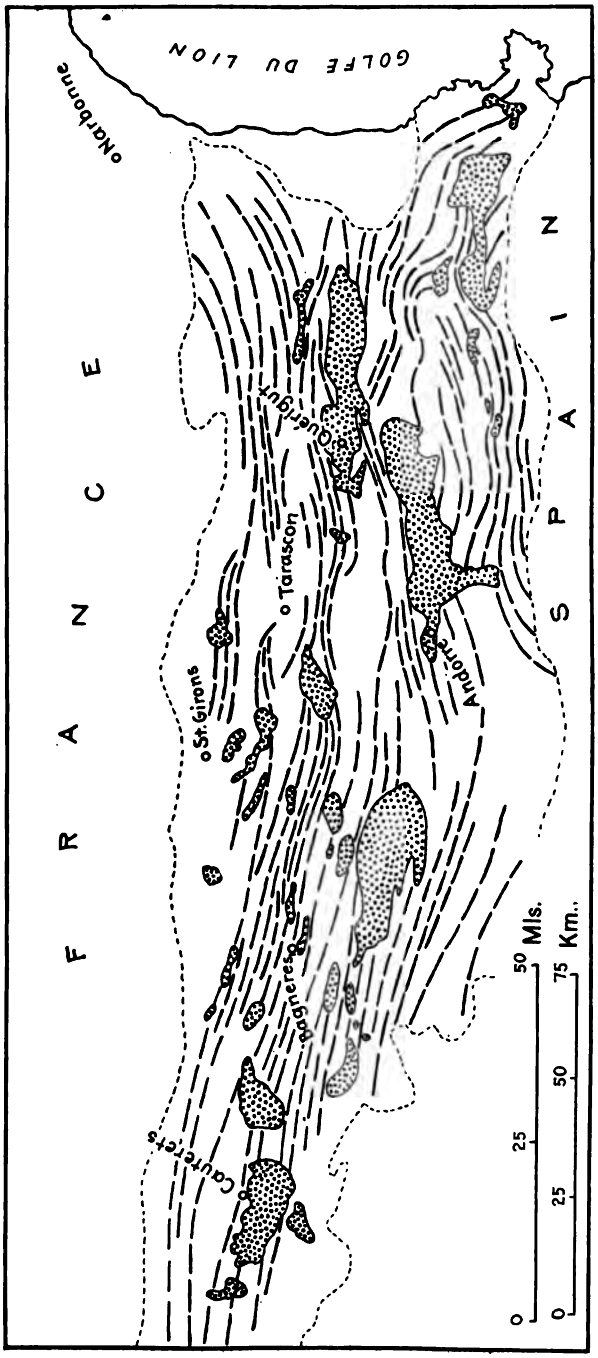


FIG. 42.—Map showing alignment of batholiths and stocks (*dotted*) in the Pyrenees, parallel to the orogenic axes, which are shown diagrammatically by broken lines.

TABLE VI

Orogenic period	Corresponding batholithic period	Region
Epi-Keewatin	Laurentian	16 districts of Lake Superior Region; Canadian shield in general.
Epi-Lower Huronian	Middle Huronian	7 districts of Lake Superior Region.
Epi-Upper Huronian	Keweenawan	2 districts of Lake Superior Region.
Epi-Grenville	Laurentian	Adirondacks, Ontario.
Pre-Cambrian	Later pre-Cambrian	Laramie Mts., Wyoming.
Epi-"Algonkian"	Later pre-Cambrian	Black Hills, S. Dakota.
Epi-"Fernandan"	Later pre-Cambrian	Central Texas.
Epi-"Algonkian"	Later pre-Cambrian	Colorado Front Range.
Epi-Shuswap terrane	Later pre-Cambrian	British Columbia.
Epi-Vishnu	Later pre-Cambrian	Grand Canyon, Ariz.
"Lower pre-Cambrian" (a)	Later "Archean"	Sweden.
"Lower pre-Cambrian" (b)	Serarchean	Sweden.
Epi-Jatulian	Post-Jatulian interval	Sweden.
Epi-Bottnian	Post-Bottnian interval	Finland,
Epi-Kalevian	Post-Kalevian interval	Finland.
Epi-Jatulian	Jotnian	Finland (Rapakivi, batholithic?).
Pre-Cambrian	Later pre-Cambrian	Brittany.
Pre-Cambrian	Later pre-Cambrian	Mt. Lofty Ranges, South Australia.
Post-Malmesbury	Later post-Malmesbury	Cape Province.
Early pre-Cambrian	Later pre-Cambrian	Shan-Tung and other districts, China.
Epi-Ordovician (?)	Taconic (?)	New York and New England.
Caledonian	Devonian (?)	Christiania region.
Caledonian	Devonian (?)	Western Norway.
Epi-Devonian	Late Devonian or Early Carboniferous.	Canadian Appalachians.
Post-Niagara	Late Silurian or Devonian	Fox Islands and Perry basin, Maine.
Hercynian	Early Carboniferous	Brittany.
Hercynian	Carboniferous	Germany.
Hercynian	Carboniferous (or Permian?)	Devon, Cornwall.
Carboniferous	Permo-Carboniferous	New South Wales.
Carboniferous	Permo-Carboniferous	Queensland.
Epi-Carboniferous	Permian	Pyrenees.
Epi-Kanieri (Mesozoic?)	Post-Kanieri (Tertiary?)	New Zealand.
Epi-Triassic	Late Jurassic	Caucasus.
Late Jurassic	Close of Jurassic	Sierra Nevada.
Late Jurassic	Close of Jurassic	Cascade Range.
Late Jurassic	Late Jurassic or Early Cretaceous.	Coast Range of British Columbia and Alaska.
Late Jurassic	Close of Jurassic	West-Kootenay District, British Columbia.
Late Jurassic	Close of Jurassic	Idaho-Montana.
Epi-Cretaceous	Early Tertiary	Patagonian Cordillera.
Epi-Cretaceous	Early Tertiary	New Mexico.
Epi-Cenomanian	Early Tertiary or Late Cretaceous.	Pyrenees.
Tertiary	Later Tertiary	Tyrol.
Mid-Miocene	Late Miocene	Washington State.
Miocene	Pliocene	Yellowstone Park (batholithic?).

partly summarize the history of the world's batholithic intrusions in relation to orogenic movements.[1]

Cross-cutting Relation to the Invaded Formations.—A leading characteristic of stock or batholith is that its contact-surfaces usually truncate the planes of stratification or of schistosity in the invaded formations.

This rule is specially patent in the published maps of subjacent bodies. Examples are reproduced in Figs. 43, 44, 45, 46, 55, 62, 64, and 164.[2]

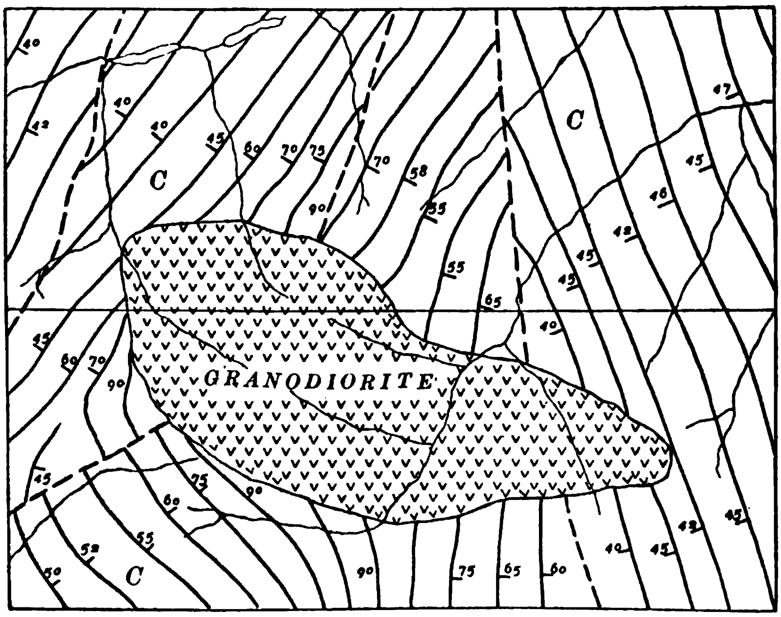


FIG. 43.—Map showing relation of the Castle Peak stock (British Columbia-Washington) to the invaded Cretaceous sandstones and argillites (*C*). Strike and dip lines solid; fault lines broken; figures show values of dip. Scale, 1:125,000.

Studies on batholiths and stocks which have been deeply canyoned by streams, and on others which have been explored underground by deep mining, show that subjacent bodies cross-cut the country rocks also in vertical sections. (See Figs. 46, 115, 168, and 169.)

[1] In the table the prefix "epi" means that the corresponding orogenic period directly succeeds the sedimentary period, the name of which follows the prefix in the first column. The "intervals" noted for the Swedish and Finnish cases are those which elapsed after the respective orogenic movements were completed and before the next recognized sedimentary series was deposited.

[2] See B. K. Emerson, Mon. 29, U. S. Geol. Survey, 1898, Plates 25, 28, 31, 32, and 34; J. C. Branner *et al.*, Santa Cruz Folio, U. S. Geol. Survey, No. 163, 1909, map and plate of structure sections.

In exceptional cases the country rocks of even post-Cambrian batholiths have been metamorphosed in such a way that these rocks show a new schistosity or cleavage running parallel to the batholithic contact (Fig. 47). The cross-cutting quality of the intrusions is then not so quickly obvious, but seldom, if ever, does it fail to appear on a close examination of the metamorphosed terrane.

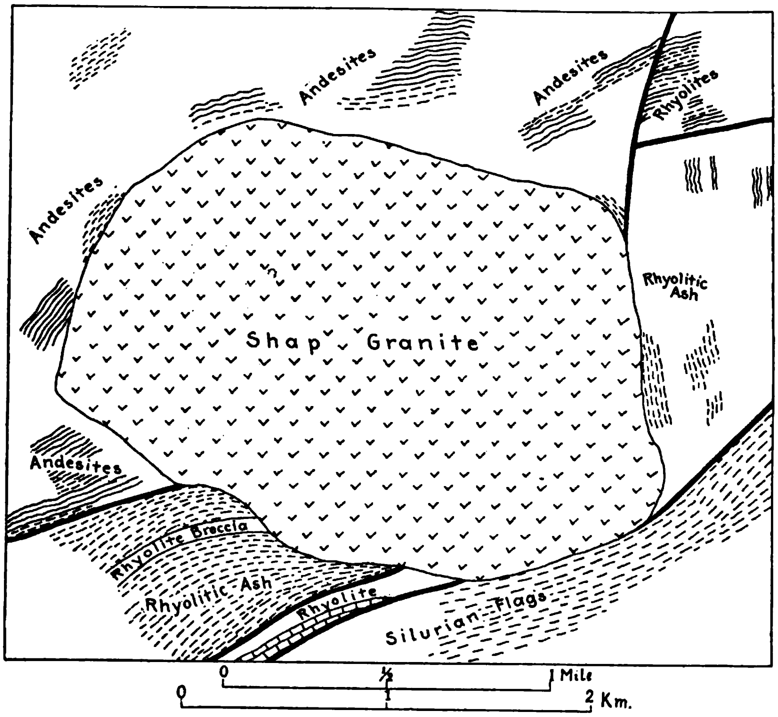


FIG. 44.—Map of the Shap granite stock, England, showing its cross-cutting character. (After A. Harker and J. E. Marr, Quart. Jour. Geol. Soc., Vol. 47, 1891, Plate 10.) Faults shown in heavy lines.

Principal Features of Roof and Walls.—The contact-surface or roof of a batholith or stock characteristically has the shape of a dome. (See Fig. 48.) The dome is, however, usually diversified by salients and re-entrants. Very often great salients of the country rocks, with the approximate shapes of inverted pyramids or of downwardly directed wedges, hang from the general roof (Figs. 49, 50, and 51). Such have been called "roof-pendants."[1] Each may be recognized as a projection of the roof rather than as inclusions of country rock, partly by its great size and, still more clearly, if the average strike of its

[1] R. A. Daly, Bull. Geol. Soc. America, Vol. 17, 1906. p. 336.

structures lies parallel to the average strike of the country rock surrounding the batholith. If such a mass were an inclusion in the once-molten magma, it would regularly be shifted or rotated out of the

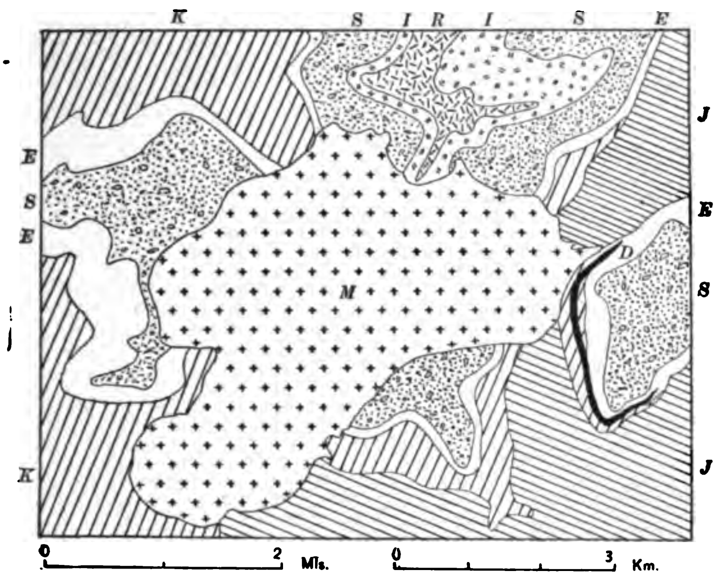


Fig. 45.—Map of monzonite stock in the Telluride quadrangle, Colorado, showing cross-cutting character. (After Telluride Folio, No. 57, U. S. G. S., 1899.) *M*, monzonite; *D*, diorite porphyry; *R*, Potosi rhyolite; *I*, Intermediate series (volcanic breccias); *S*, San Juan tuffs; *E*, Eocene conglomerate; *K*, Cretaceous shale and sandstone; *J*, Jurassic shale, sandstone, and limestone. *M*, *D*, *R*, *I*, and *S* are Tertiary; the monzonite cuts all the bedded rocks.

regional strike. Further, as noted in Chapter X, it would be practically impossible for a very large inclusion to remain suspended in a molten batholith, even if it were as viscous as hard pitch.

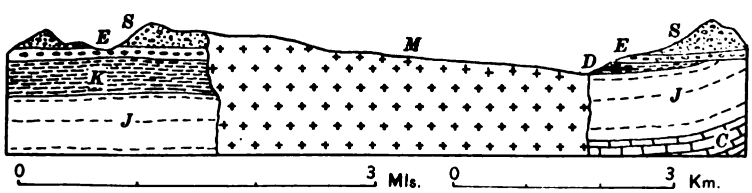


Fig. 46.—East-west section through stock mapped in Fig. 45, showing cross-cutting in vertical plane.

Again, batholithic roofs often deviate systematically from the pure domical shape because of the presence of re-entrants composed of the batholithic material. These projections of the igneous mass have been called "cupolas," from the analogous relation of an artificial cupola to the building of which it is a part.[1] Many stocks are cupolas on batholiths. Examples are noted in Figs. 50 and 51.

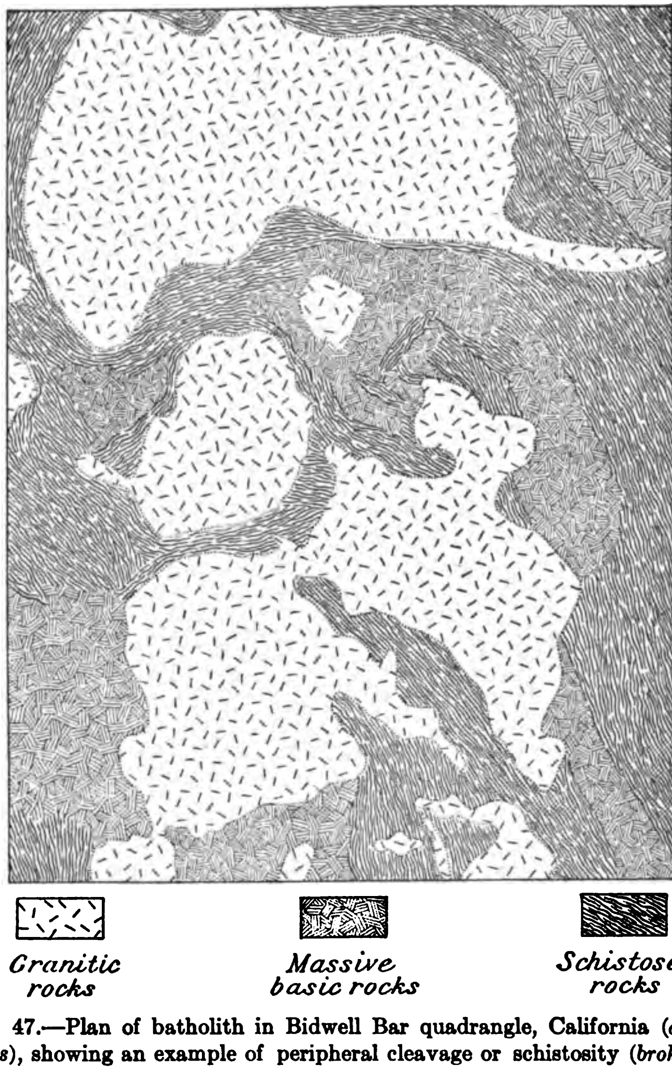


FIG. 47.—Plan of batholith in Bidwell Bar quadrangle, California (*divergent hachures*), showing an example of peripheral cleavage or schistosity (*broken lines in country rocks*). (After Bidwell Bar Folio, No. 43, U. S. G. S., 1898.) Scale, 1:490,000.

Possibly some cupolas have been open to the sky, so that a subjacent body may be locally roofless. This has been a rare case, except,

[1] R. A. Daly, Proc. Amer. Acad. Arts and Sciences, Vol. 47, 1911, p. 69.

of course, where volcanic vents of the central type have been fed directly from a batholith.

Only quite seldom is it possible to follow a plutonic contact vertically for more than a few hundred feet as it pitches into the invisible depths. In general, however, the roof is marked off from the "walls" of the igneous body by a relatively sharp increase in the average dip of the contact-surface at the edge of the roof. Below that edge the average angle of dip is always more than forty-five degrees, and in most cases seems to average well over sixty degrees. In brief, the walls of a typical subjacent body are highly inclined.

Though the main walls of a batholith are often broken by apophyses, they must be described as, on the whole, remarkably smooth. On the

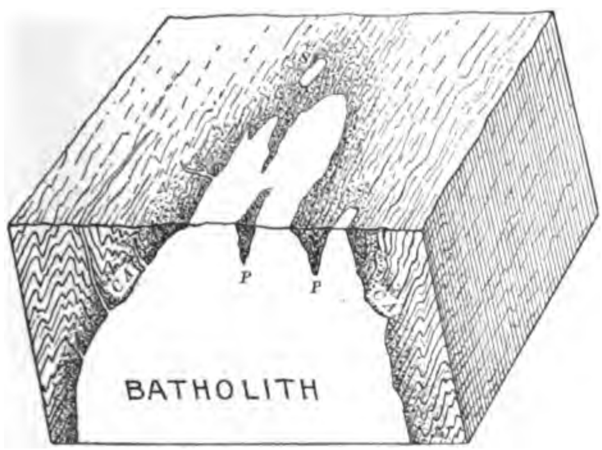


FIG. 48.—Diagram showing features of an ideal batholith. *P*, roof-pendants; *CA*, aureole of contact metamorphism in folded sediments; *S*, satellitic stock.

accurate maps now published, the contact lines of deeply eroded stock or batholith are almost always flowing lines. This is another of the fundamental facts which has to be explained by a stable petrogenic theory. Illustrations are given in Figs. 39, 43, and 44.

Downward Enlargement.—In general, the average dips of the main (molar) contact surface of stock or batholith are quaquaversal. The few recorded exceptions to that rule refer to outcrops which are limited both vertically and horizontally. It is quite possible that these contact surfaces would also show quaquaversal dips if they were better exposed, especially in depth. In any case, the rule is clear that the greater intrusive bodies enlarge downwardly. The enlargement in the horizontal section is rapid at first, that is, to the "edge" of the roof; it is usually then much slower to the deepest levels exposed by natural erosion or inferred from mining or drilling. In all the greater

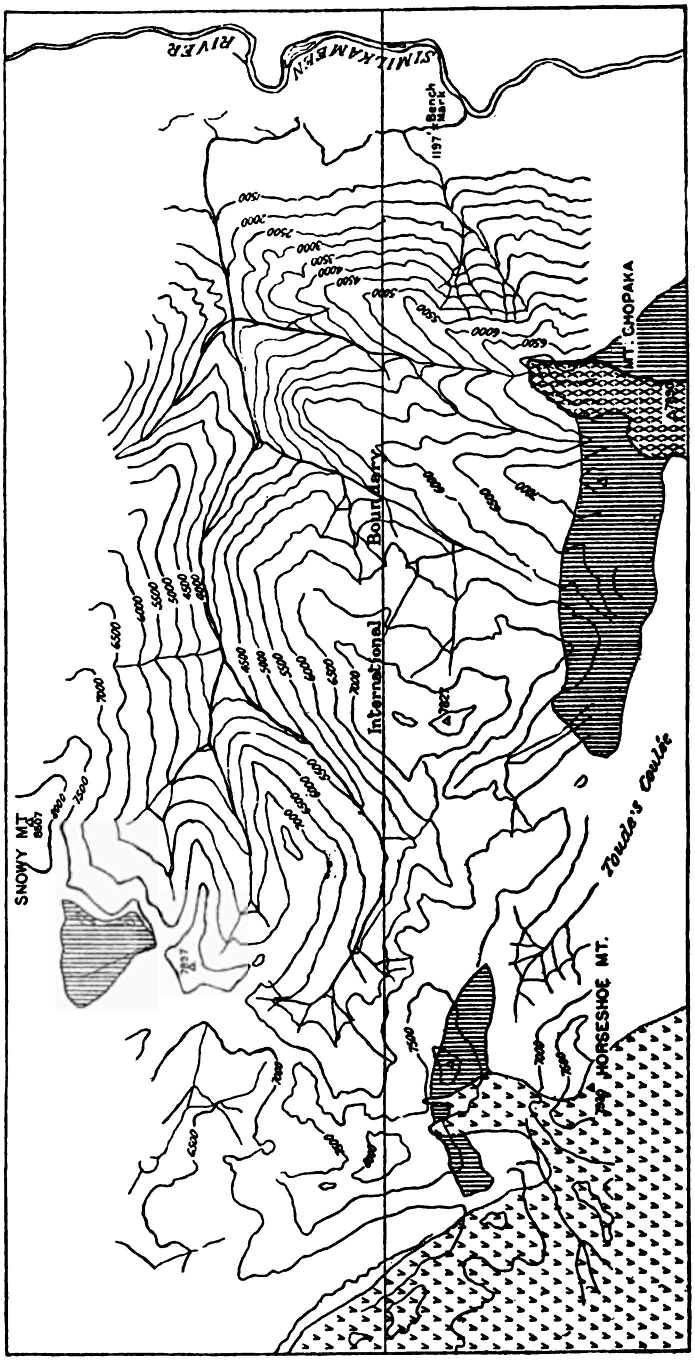


FIG. 49.—Roof-pendants in the Similkameen granodiorite batholith (*blank*), British Columbia-United States boundary. (R. A. Daly, Memoir 38, Geol. Surv. Canada, 1912, p. 430.) *Inverted carets*, Cathedral granite batholith; *vertical lining*, schists of roof-pendants; *crosses*, gabbro and dunite of pendant. Scale, 1:120,000; contours in feet.

subjacent bodies the enlargement doubtless continues for one or more miles in depth, but it is hardly probable that the increase in the hori-

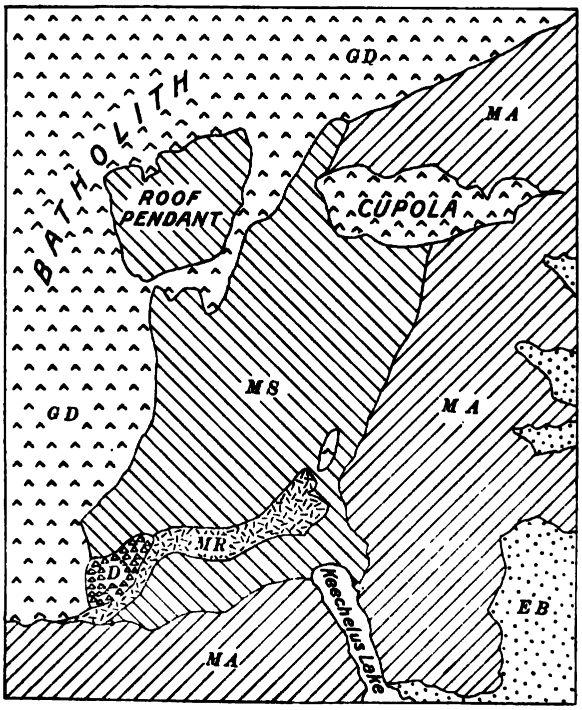


FIG. 50.—Map showing roof-pendant in, and cupola stock satellitic from, the Snoqualmie batholith, Washington State. (After Snoqualmie Folio, No. 139, U. S. G. S., 1906.) *GD*, granodiorite; *D*, diorite; *MA*, andesite; *MR*, rhyolite; *MS*, slate, etc.; *EB*, Teanaway basalt (Eocene). All formations except *EB* are of Miocene age. Scale, 1:210,000.

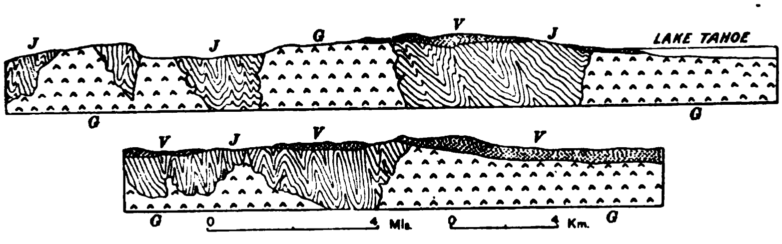


FIG. 51.—Transverse sections in the Sierra Nevada, California, showing cupola stocks and roof-pendants in a granodiorite batholith (*G*). (After Truckee Folio, No. 39, U. S. G. S., 1897.) *V*, Neocene volcanics, chiefly andesites; *J*, Jura-Trias (?) slate and schist.

zontal section continues indefinitely. Figs. 52, 53, 54, 55, 56, 57, 58, 40, 43, and 49 are maps and sections (in part hypothetical) of a series

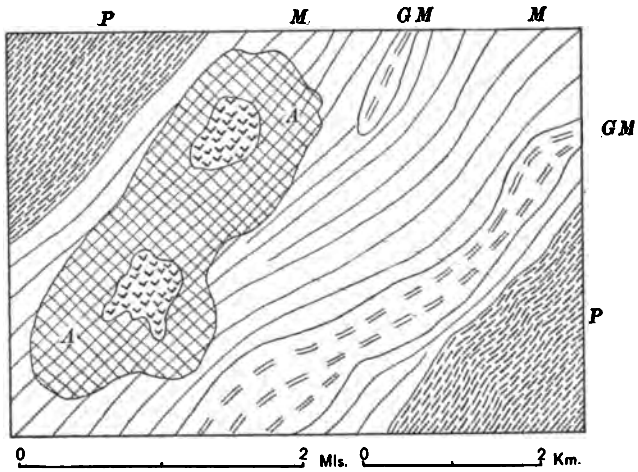


FIG. 52.—Map showing incipient unroofing of a granite stock in Saxony (After Geyer-Ehrenfriedersdorf Sektion of the Geol. Spezialkarte.) *Inverted carets*, granite; *A*, metamorphic aureole in muscovite schist; *P*, phyllite; *M*, muscovite schist; *GM*, gneissic mica schist. Two bosses of the granite body are exposed by erosion; the great width of *A* is to be explained by the rapid enlargement of these bosses in depth. (Compare K. Dalmer, Zeit. für prak. Geol., Bd. 8, 1900, p. 297.)

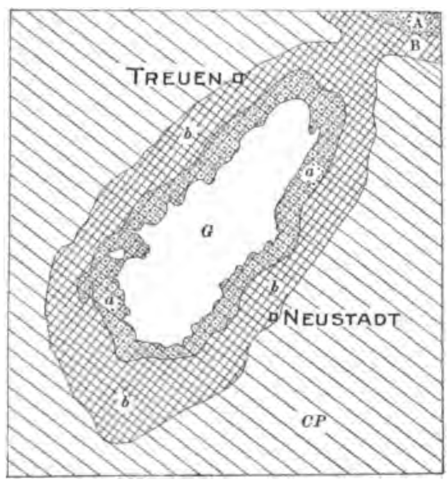


FIG. 53.—Map showing partial unroofing of a large granite stock in Saxony. (After Geol. Spezialkarte des Kön. Sachsens—Treuen and neighboring Sektionen.) *G*, granite; *CP*, Cambrian and older argillite and phyllite; *a*, inner metamorphic aureole; *b*, outer metamorphic aureole; *A*, inner aureole of Kirchberg-Schneeberg granite batholith; *B*, outer aureole of the same. The great width of *a* and *b* suggests that much of the roof of the stock still remains. Scale, 1:275,000.

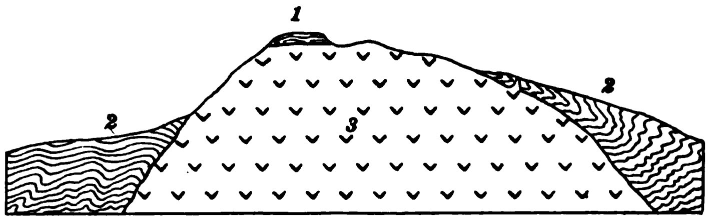


FIG. 54.—Section showing partial unroofing of a granite stock (*3*) in the Seward Peninsula, Alaska. (After A. Knopf, Bull. 358, U. S. G. S., 1908, p. 27.) *1*, schists; *2*, contorted limestone. Horizontal scale, 1:84,000; vertical scale, 1:60,000.

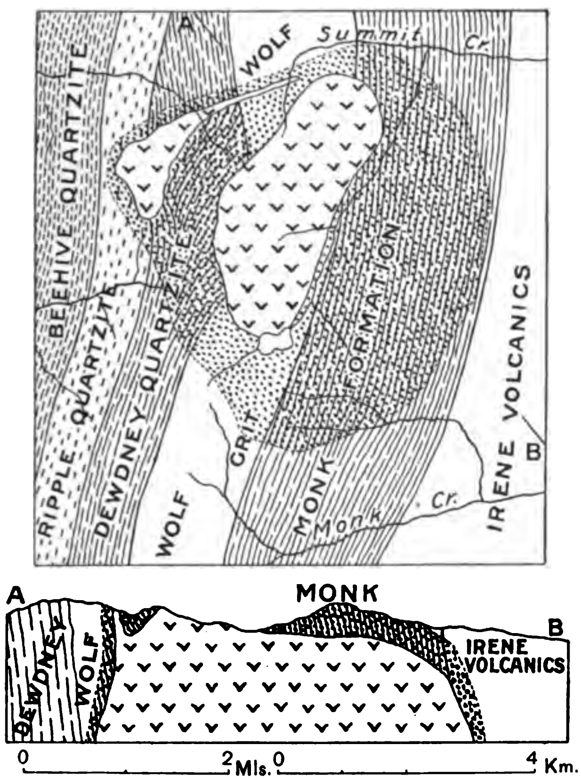


FIG. 55.—Map and section showing cross-cutting character and downward enlargement of a granite stock (*inverted carets*) in the Selkirk Mts., near the 49th Parallel. (R. A. Daly, Memoir 38, Geol. Surv. Canada, 1912, p. 299.) The broad aureole of contact metamorphism and shattering in the nearly vertical strata is shown with dots.

of stocks and batholiths showing advance in erosional unroofing, with the implication of downward enlargement. Figs. 59, 60 and 61 illus-

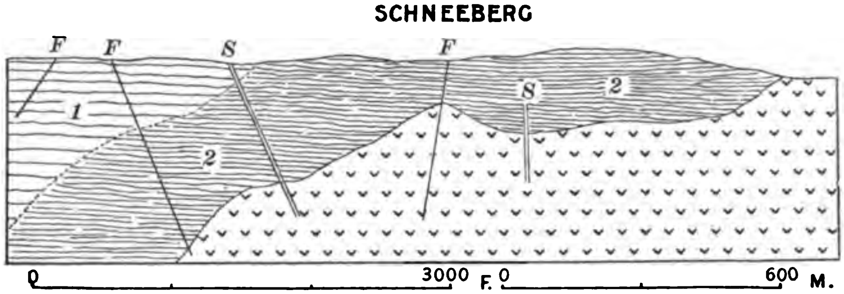


FIG. 56.—Section showing how mining has proved downward enlargement for a German granite batholith (*inverted carets*). (After Geol. Spezialkarte des Kön. Sachsens, Sekt. Schneeberg, and R. Lepsius, Geologie von Deutschland (Engelmann).) *1*, outer metamorphic aureole, in phyllite; *2*, inner metamorphic aureole, in phyllite; *S*, mining shafts; *F*, Flötze.

trate well exposed contacts showing quaquaversal dips to considerable depths.

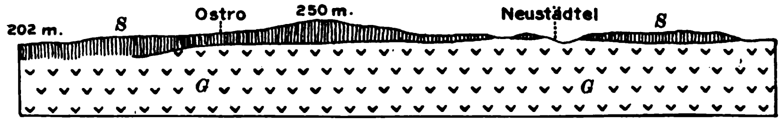


FIG. 57.—Demonstrated profile of the Lausitz granite batholith (*G*), Germany, which is intrusive into metamorphosed graywackes (*S*). (Same ref. as for Fig. 56, Sekt. Kloster St. Marienstern.) Horizontal scale, 1:86,000; vertical scale 1:172,000.

The attempt to "extrapolate" from the known facts, so as to construct the probable type for stock or batholith in great depth, is,

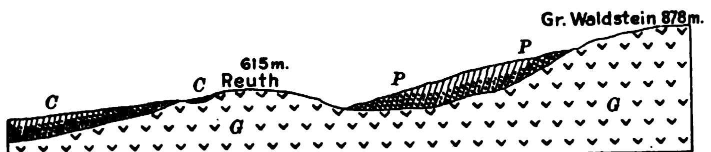


FIG. 58.—Demonstrated profile of a granite batholith (*G*) in the Fichtelgebirge. (After R. Rüdemann, Neues Jahrb. für Miner., B. B. 5, 1887, p. 674, and R. Lepsius, Geologie von Deutschland (Engelmann).) *C*, Cambrian slates and metamorphosed equivalent (*dots*); *P*, Phyllite and metamorphosed equivalent (*dots*).

of course, to enter the realm of hypothesis. Nevertheless, this problem is at the very heart of petrogenic philosophy. It must be attacked if petrology is to make essential progress. The writer believes it can be attacked indirectly and that the positive results can justify this venture into the field of speculation. The conception that batholiths are bottomless (in the sense that its visible country-rocks do not extend beneath it) seems to accord with the vast multitude of facts embodied in igneous petrography and geology. No rival conception has ever succeeded in so thoroughly explaining these myriad facts. The preferred hypothesis has, in the writer's opinion, a sanction which can probably become of the same order as the wave theory of light or the atomic theory of matter. Yet the conception that the typical

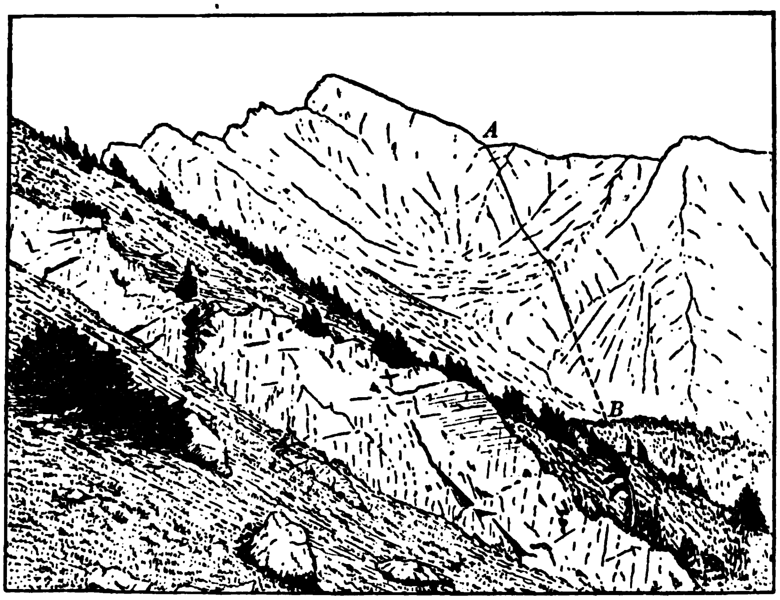


Fig. 59.—Plunging contact (*AB*) at south side of granodiorite stock (left) cutting Cretaceous sediments (right) at Castle Peak, British Columbia. (R. A. Daly, Memoir 38, Geol. Surv. Canada, 1912, p. 498.) The vertical distance between *A* and *B* levels is 800 ft. Traced from a photograph.

batholith is bottomless *is* hypothetical and, as such, its consideration is deferred to later chapters in this book.

Replacement of Invaded Formation.—As a guide to further thought along this line, another fact may here be appropriately mentioned. Batholiths and stocks *appear* to have replaced their respective country rocks in the act of intrusion. This statement has the smack of the subjective, but its subjectivity is that of common sense reacting on the facts of nature. Just as surely as the roof-rock of a laccolith appears to have been *displaced* in the formation of the laccolithic chamber, so the roof-rock of a batholith appears to have been *replaced* in the development of the upper part of the batholithic chamber. The laccolithic magma has lifted or thrust away the roof-rock to make room for itself. In no case has the magma of a typical batholith reached its level registered in the general mass of visible plutonic rock by merely lifting the roof-rock or by thrusting it aside. The emplacement of each batholith has been a relatively quiet process, unaccompanied by any such colossal movements in the other parts

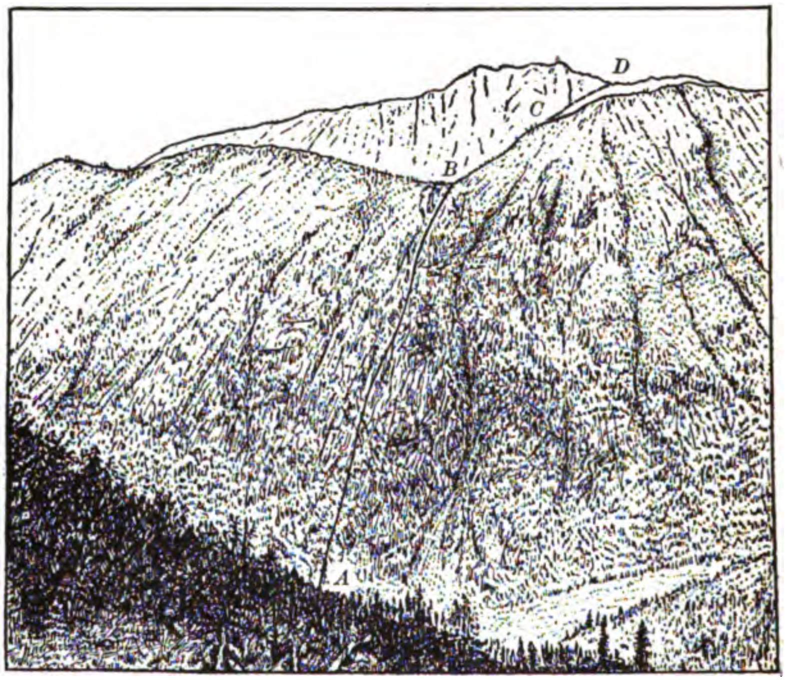


Fig. 60.—Plunging contact *ABCD* at north of same stock as that shown in Fig. 59. Granodiorite on the right; Cretaceous sediments on the left. The vertical distance between the *A* and *B* levels is 1,700 ft. Traced from a photograph.

of the earth's crust as would be required to form the huge chamber by the "laccolithic" mode of intrusion.

Plutonic geology has already supplied hundreds of examples. Some which have undergone detailed study may be recalled: the composite stock at Ascutney Mountain, Vermont (Fig. 64); the wonderfully exposed stock at Castle Peak, Hozomeen Range in British Columbia (Figs. 43, 59, 60, and 61); a stock in the Telluride quadrangle, Colorado (Figs. 45, 46); the stock at Marysville, Montana (Figs. 114 and 115); many stocks and small batholiths in Brittany and in the Pyrenees (Figs. 39, 42, 62, and 63); and the satellites of the Bayonne batholith of British Columbia (Fig. 55). A typical record is here quoted

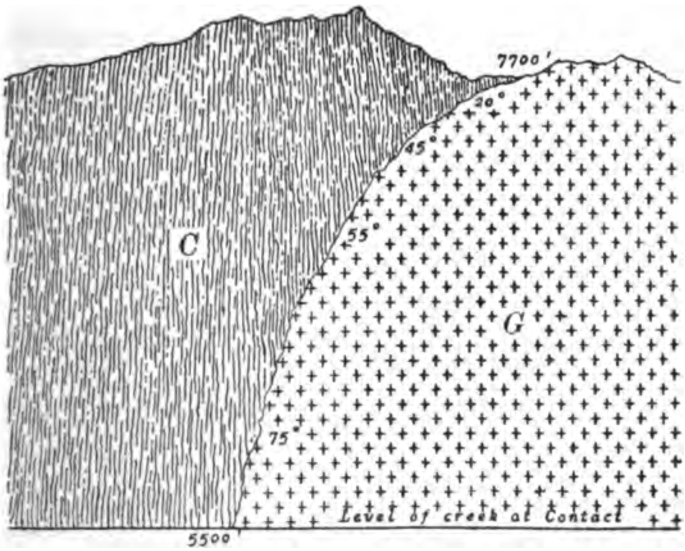


FIG. 61.—Canyon-wall section at north of same stock as that shown in Fig. 59; from a field sketch. *G*, Granodiorite; *C*, Cretaceous argillite. Elevations in feet; dips in degrees.

from Cushing's report on the geology of the Thousand Islands region of New York State. Concerning the Picton granite, he writes: "Our

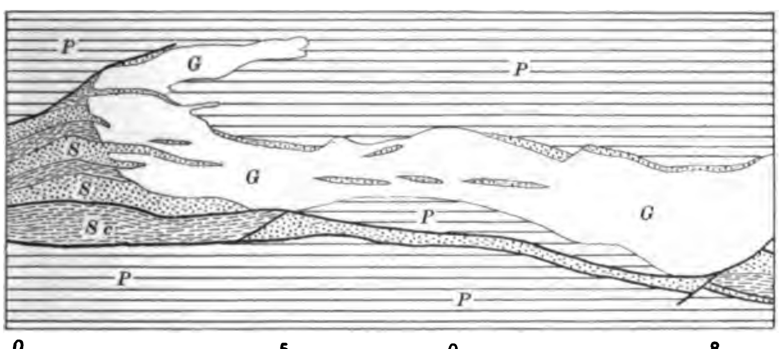


FIG. 62.—Map showing replacement of sediments by a granite batholith (*G*) in Brittany. (After C. Barrois, Annales soc. géol. du Nord, Vol. 21, 1893, p. 240.) *Sc*, Silurian and Devonian slates; *S*, Silurian sandstones; *P*, St. Lô phyllites. Note the preservation of strike in the sandstones.

strikes and dips, read on the rocks in the field, gave absolutely concordant results as we passed from one inclusion [roof-pendant] to another, results also concordant with the readings obtained on the same rocks beyond the reach of the intrusion. We were able to map the original belts of Grenville quartzite and schist, and the intrusions of Laurentian granite gneiss, as accurately as though the Picton granite was not present, so little had they been disturbed by the intrusion."[1]

The cross-cutting quality of the batholiths, where viewed in plan or in section; the nature and position of roof-pendants and of magmatic cupolas; the slight influence of batholiths on the tectonic axes of their respective country rocks; the general failure of circumferential faults or axes of warping about batholiths, and the fact that none

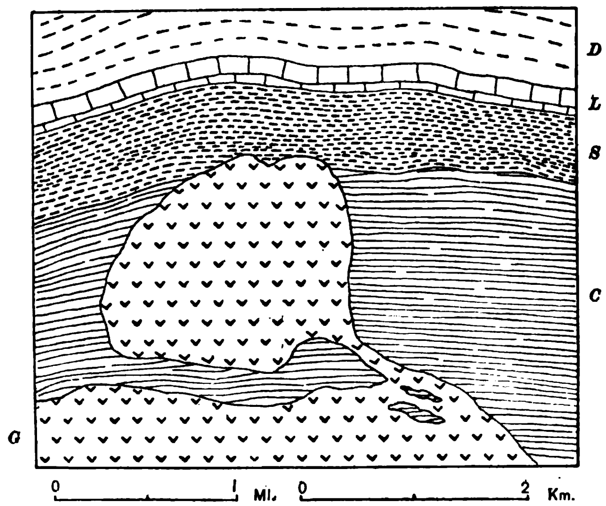


FIG. 63.—Map showing replacement of sediments by the Cauterets granite (*G*) of the Pyrenees. (After A. Bresson, Bull. serv. carte géol. France, Vol. 14, 1903, Pl. V, Fig. 1.) *C*, Carboniferous quartzite, etc.; *S*, Carboniferous slate, etc.; *L*, Devonian limestone; *D*, Devonian graywacke, etc.

of these bodies has yet been shown to have a bottom—all these facts are opposed to the application of the "laccolithic" mechanism in the interpretation of subjacent bodies. On the other hand, the direct field observations favor the interpretation that the upper part of each subjacent body has been emplaced by a kind of corrosion on a huge scale. How this replacement has taken place is a matter for theoretical discussion and therefore one outside the special scope of the present chapter, which is primarily engaged in pointing out the essential observations which have been actually made concerning subjacent bodies.

[1] H. P. Cushing, Bull. 145, New York State Museum, 1910, p. 43.

Chemical Composition of Subjacent Bodies.—The chemical variation in a stock or batholith is often considerable but the average composition is approximately determinable so far as the outcrop is concerned. In the following section of this chapter the statements regarding chemical composition refer to such averages. Some discussion of the variations observed in individual bodies will be found in later chapters.

The larger subjacent masses are usually composed of granite, though granodiorite, quartz diorite, and syenite batholiths are known.

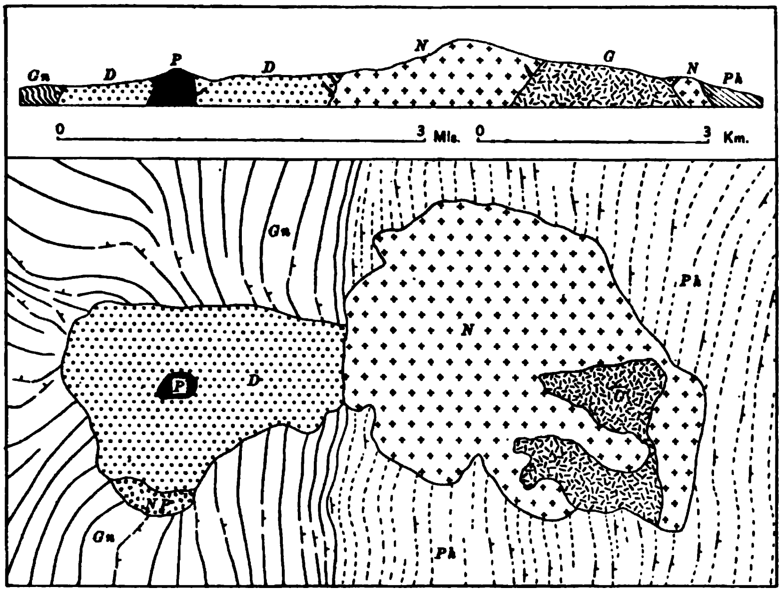


FIG. 64.—Map and section showing replacement of phyllites and gneisses by the composite stock at Mt. Ascutney, Vermont. (R. A. Daly, Bull. 209, U. S. G. S., 1903.) *G*, biotite granite stock; *N*, nordmarkite stock; *NP*, nordmarkite porphyry and paisanite; *P*, pulaskite; *D*, diorite stock, with gabbroid and essexitic phases; *Ph*, phyllites with thin limestone interbeds; *Gn*, gneisses, with thick limestone pods interbedded. Symbol for strike and dip.

It is an open question whether any other plutonic type composes a true batholith, that is, a subjacent body more than 100 square kilometers in total area of exposure. The great gabbro mass mapped in the Roseburg folio of the United States Geological Survey covers more than 300 square kilometers (150 square miles), but its relations to the surrounding Tertiary sediments suggest that this body may be a huge laccolith. (See structure sections by J. S. Diller in the folio mentioned.) The Duluth gabbro covers about 6000 square kilometers (2400 square miles) but it is regarded as a laccolith by Van Hise and Leith.[1] Ramsay and Hackman make a similar interpretation of the huge mass of nephelite syenite, urtite, etc., in the Kola peninsula of Lappland.[2] Possibly the vast bodies of anorthosite in eastern Canada, in New York State, and elsewhere, are also laccolithic, but little can yet be definitely affirmed as to the intrusive mechanism of these extraordinary bodies, whose true character is, in this and other respects, one of the deepest mysteries of petrology. (See Chapter XV, page 321.)

The large intrusions of alkaline rock near Julianehaab, Greenland, are described by Ussing as batholiths; yet certain of their structural relations and the character of their magmatic differentiation seem to indicate a chonolithic or laccolithic origin for each of these masses.[3] These magmas have performed a limited amount of magmatic stoping and it was here that Ussing became an independent author of the stoping theory. Yet the enlargement of the magmatic chambers by that method was probably moderate. One must believe that very long-continued stoping of such silicious rocks as the sandstone and ancient granite intruded by the dominant foyaitic magma would generate acid phases in volumes much greater than those actually found.

A review of other examples of the abnormally constituted, greater massifs, with respect to such structural relations as can actually be observed, shows that the mere areal extent of a "plutonic" mass cannot be taken as a sure evidence of its "bottomless," batholithic character. The sill at Hopetown, South Africa, is known to cover more than 5000 square miles.[4] If it were a few thousand feet thick, instead of a few hundred feet, that body could doubtless have crystallized (like the actual Bushveldt laccolith) with the texture and coarse grain of the normal plutonic rock. If, in addition, erosion had not exposed the floor of the sheet, it might have deceptively resembled a true batholith.

In average composition individual stocks have more variety than that characterizing the larger subjacent bodies. Besides granites, granodiorites, quartz diorites, and syenites, the list of types recorded as forming stocks includes gabbro, norite, quartz gabbro, diorite, nephelite syenite, shonkinite, or their porphyritic equivalents.

[1] C. R. Van Hise and C. K. Leith, Monograph 52, U. S. Geol. Survey, 1911, p. 372.

[2] W. Ramsay and V. Hackman, Fennia, Vol. 11, Part 2, 1894, p. 96.

[3] See N. V. Ussing, Meddelelser om Grönland, Vol. 38, 1911, pp. 38, 49, 50, 68, 251–5, 290, and Plate 6.

[4] A. W. Rogers and A. L. du Toit, Geology of Cape Colony, 2d edition, London, 1909, p. 261.

Classification of Stocks and Batholiths

Simple stocks are composed of material intruded in one period of irruption. Types are illustrated in Figs. 39, 42–46, 50–55, 59, 60, and 61.

On the analogy of multiple dikes, a *multiple stock* may be con-

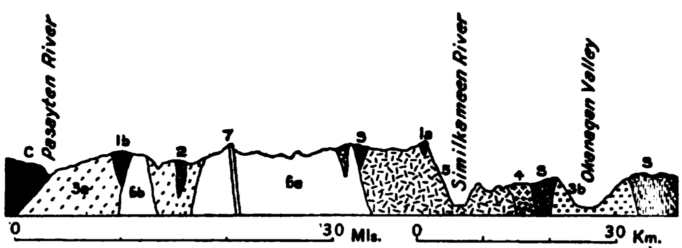


Fig. 65.—Section of Okanagan composite batholith at 49th Parallel. (R. A. Daly, Memoir 38, Geol. Surv. Canada, 1912, p. 426.) *S*, Paleozoic schist, limestone, quartzite, etc.; *C*, Cretaceous sandstone and volcanic breccia; *1a*, Chopaka peridotite; *1b*, basic complex (gabbro, hornblendite, etc.); *2*, Ashnola gabbro; *3a*, Remmel granodiorite (gneissic); *3b*, Osoyoos granodiorite (gneissic); *4*, Kruger nephelite syenite and malignite; *5*, Similkameen granodiorite; *6a*, Cathedral granite, older phase; *6b*, Park granite; *7*, Cathedral granite, younger phase. The igneous rocks are numbered in the order of intrusion. Vertical exaggeration of about 5 to 1.

ceived, namely, one which is composed of uniform material demonstrably intruded in two or more distinct stages of one eruptive period. Apparently no example is on record.

A *composite stock* is composed of materials demonstrably intruded

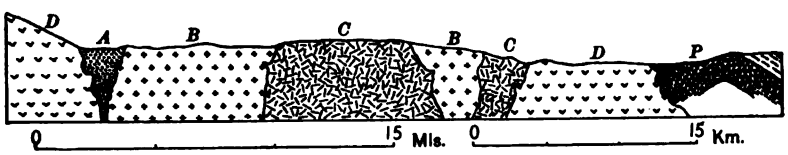


Fig. 66.—Section of the composite batholith of New England, New South Wales. (After E. C. Andrews, Records, Geol. Surv. N. S. W., Vol. 8, Pt. 2, 1905, Fig. 7.) *P*, Permo-Carboniferous sediments; *A*, Dark porphyries; *B*, "Blue granite"; *C*, Sphene-granite porphyry; *D*, "Acid granite." The rocks are named in the order of intrusion. Scale approximate.

in two or more distinct stages of one eruptive period, the magmas of the different intrusions having different compositions. A number of examples are known. (See Figs. 64 and 181.)

In corresponding fashion, *simple* and *composite* batholiths may be distinguished. No *multiple* batholith has been described and there is reason to doubt that one shall ever be discovered. During the extremely long time represented in the crystallization of part of a large magma chamber, the forces leading to the differentiation of the residual liquid would tend to produce magma differing chemically from that already solidified. In general, therefore, the result of renewed intrusion during a single petrogenic cycle should be a composite, not a multiple, batholith.

Simple batholiths are illustrated in Figs. 40–2, 47, 57, and 58.

The greatest exposed post-Cambrian composite batholith is doubtless that forming the greater part of the Coast Range of British Columbia and Alaska (Fig. 37). Another example, perhaps an outlier of the vast body just mentioned, has been sectioned and described by the writer under the name, "Okanagan composite batholith"[1] (Fig. 65). Nearly all of the larger plutonic masses in the North American Cordillera seem to be of the composite class. To this class the writer is disposed to refer the intrusive complex of the Christiania Region, made classic by the writings of Brögger.[2] Figs. 66 and 116 illustrate composite batholiths in Australia and Scotland.

[1] R. A. Daly, Bull. Geol. Soc. Amer., Vol. 17, 1906, p. 329.

[2] W. C. Brögger, Die Eruptivgesteine des Kristianiagebietes, Vol. 1, 1894, and Vol. 2, 1895.

CHAPTER VII

EXTRUSIVE BODIES

Classification

As far as possible the classification of the extrusive bodies should be rigorously tied to field observations. But experience shows that little progress can be made without some immediate interpretation of the simple observed facts. It is obvious that a *complete* classification of the known extrusive bodies cannot be made without a preliminary, very thorough exercise of the faculty of interpretation. That means the use of principles which, by their very nature, are not to be deduced from field facts alone. The classification to be outlined in the present chapter, being founded primarily on field observations, can be neither complete nor wholly genetic. It will serve, however, to exhibit the leading facts which, with a multitude of others, are capable of fuller and more systematic description after the theory of igneous action has been reviewed.

Three principal groups of extrusive masses have been recognized, the distinction in each case being founded on the mode of extrusion. Two of the groups, respectively formed by "fissure" eruption and by "central" eruption, are regularly named and discussed in modern textbooks on geology. The third group of volcanic masses is not generally appreciated at its apparent value; it includes those bodies of lava formed by what is here called "de-roofing" eruption. As indicated below, these three types of eruption are transitional into each other, but the recognition of the pure types is none the less helpful in forming a basis for volcanic theory.

I. Fissure Eruptions

The simplest mode of extrusion is illustrated in the greatest basaltic fields. As a rule, the lavas have there issued quietly, without explosion of violence sufficient to form dominant layers of tuff or other pyroclastic material. However, occasional ash-beds locally interrupting the lava flows represent temporary eruption of the familiar "central" type. The famous eruption at the Icelandic Skaptar Jökull fissure during 1783, the most imposing historic example, typified this subordinate part of pyroclastic deposits in basaltic plateaus.

Table X, page 191, lists some of the more important fissure eruptions. Those of Tertiary date are generally little deformed and merit the common name, plateau basalts. The fields celebrated for their extent are those in India (Fig. 67) and the northwestern United States. Their only rival among the post-Jurassic fields is probably that of the North Atlantic. Even the remnants of the plateau basalts

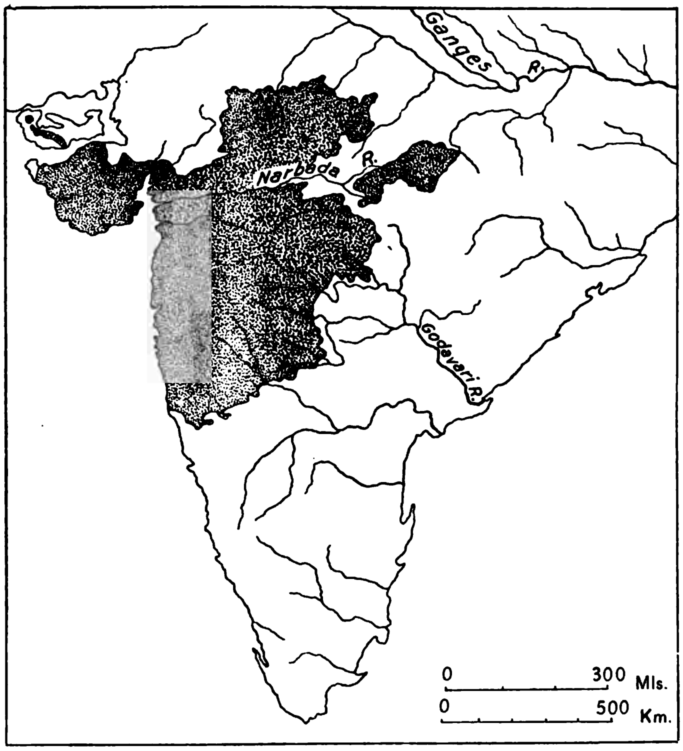


FIG. 67.—Map showing distribution of the Deccan traps (*dotted*).

still visible after the late-Tertiary subsidence of this ocean basin are considerable, as shown in Thoroddsen's table:

	Estimated Areas (sq. km.)
Scotland and Ireland	10,000
Faroe Islands	1,325
Iceland	104,785
East coast of Greenland	20,000+

It is possible that the North Atlantic Tertiary basalts have covered an area totalling 500,000 square kilometers. Those, together with the basalts of the northwestern United States and the Deccan, represent a grand total of nearly 1,500,000 square kilometers or one-third of the area estimated by von Tillo to be covered by all the "young" volcanic masses of the continents and islands.

Observed thicknesses for the plateau basalts reach high figures. The maximum proved for the Teanaway basalt (Eocene) in Washington State is 6000 feet (1830 meters). The overlying Yakima basalt

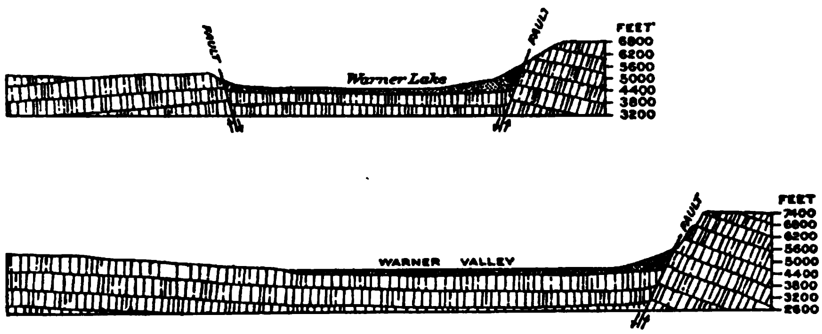


FIG. 68.—Sections showing great thickness of Tertiary fissure eruptions of basalt in Oregon. (After G. A. Waring, Water Supply Paper 220, U. S. G. S., 1908, Pl. 10.)

(Miocene) is more, perhaps much more, than 2000 feet (600 meters) in thickness at the Yakima River canyon. The Oregon basalt is also very thick (Fig. 68). A. Geikie estimates the maximum thickness of the Iceland basalts at 3000 meters. That of the plateau basalt in northwestern Greenland is more than 1200 meters. The Deccan traps are locally more than 6000 (1830 meters) thick.

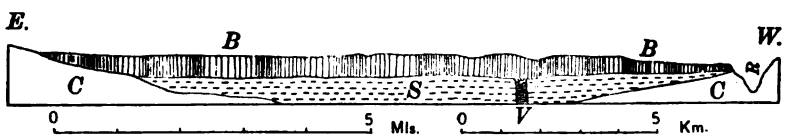


FIG. 69.—Section of great fissure eruption in Williams Canyon, Arizona. (After W. T. Lee, Bull. 352, U. S. G. S., 1908, p. 54.) *C*, crystalline rocks; *S*, sand and gravel; *B*, massive flow of basalt, 800 ft. thick; *V*, vent of the flow, 400 ft. in diameter.

The thickness of individual flows in such terranes seldom surpasses 100 meters. In the United States the average thickness is probably less than 15 meters. The observed averages for the Deccan flows in the Bhor and Thal Ghâts are respectively 19 meters and 26 meters, but these values are said to be too high, on account of the difficulty of distinguishing the flows in many cases.[1] Thoroddsen states that

[1] R. D. Oldham, A Manual of the Geology of India, 2nd ed., Calcutta, 1893, p. 261.

the Icelandic flows are generally from 5 to 10 meters thick. The South African flows seem to have nearly the same average dimension. Where, however, the eruption takes place in a valley the lava may attain much greater depth. Lee has mapped a remarkable case at Williams canyon, Arizona, where the basalt is locally 800 feet (240 meters) thick and covers an area 14 kilometers broad by 22 kilometers in length. This flow has a well-exposed feeder with the unusual width of 400 feet (120 meters) (Fig. 69).

Thoroddsen gives some illustrations of the lengths, areas, volumes, and surface slopes of sample Icelandic flows:

Flow	Length, km.	Area, sq. km.	Volume, cu. met.	Slope
Laki fissure (1783 eruption)........	90	565	12,320,000,000	....
Veidivatnahraun (prehistoric)......	150	1,080	43,160,000,000	5′
Frambruni (prehistoric)...........	110	465	23,250,000,000	30–41′
Eldgjá (about 930 A.D.)..........	....	....	9,325,000,000	....

He also estimates the volume of the greatest liparitic flow in Iceland (Hrafntinnihraun) to be about 500,000,000 cubic meters and thus insignificant when compared with the basalt floods.

The foregoing table and that on page 290 illustrate the noteworthy contrast in volume between flows in a basaltic plateau and those emanating at "central" vents.

The feeding dikes of the plateaus are numerous but narrow; the width probably averages less than 10 meters and seldom reaches 50 meters (Fig. 70). The narrowness of the feeding fissures is a direct evidence of the relative rapidity of these extrusions. If the magma remained stagnant many days or weeks in such narrow vents it would necessarily solidify and seal the fissures. These could then be reopened for continued eruption only by explosion or by a remelting of the congealed rock. Neither of these events has regularly occurred in the fields of plateau basalts. It seems to follow that, in general, fissure eruption is a sudden act.

The relation of basaltic floods to crustal stresses is briefly discussed in Chapter IX, pages 186 and 191.

While the vast majority of fissure eruptions are basaltic, other petrographic types are represented. The rhyolite of Corsica appears to have welled up through numerous fissures rather than pipes (Fig. 31, page 83). Gregory states that trachyte, andesite, and basalt are all represented in the fissure eruptions of the Great Rift in Eastern Africa.[1] Many small phonolitic flows, both in Europe and in America, have emanated from fissures. In fact, it is quite possible that all of the clans

[1] J. W. Gregory, The Great Rift Valley, London, 1896, p. 235.

are represented in extrusions of this kind. Yet basalt doubtless composes at least 95 per cent. of the total known volume of fissure eruptives. The significance of this important fact will be noted in Chapter VIII.

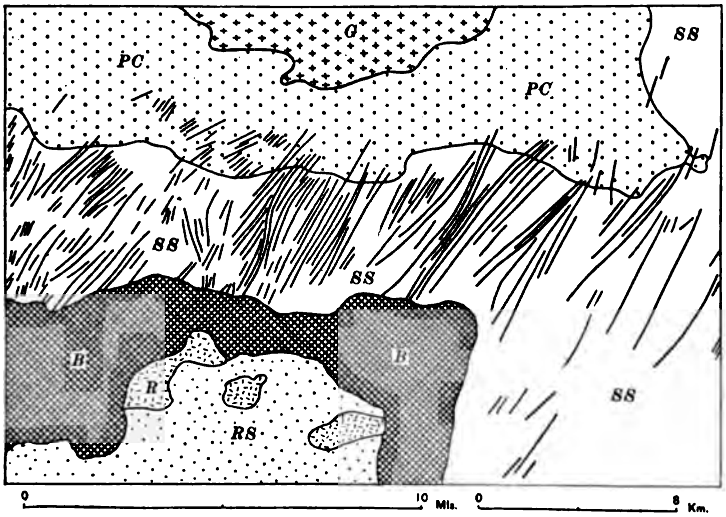


FIG. 70.—Map of dike feeders of Tertiary fissure eruptions near Mt. Stuart, Washington. (After Mt. Stuart Folio, No. 106, U. S. G. S., 1904.) *PC*, pre-Tertiary complex (peridotite and greenstone); *G*, Mt. Stuart granodiorite; *SS*, Eocene Swauk sandstone; *B*, Eocene basaltic fissure eruptions; their feeders shown by lines; *RS*, Eocene Roslyn sandstone and shale; *R*, Pliocene (?) rhyolite.

II. EXTRUSION BY DE-ROOFING

We have seen that the covers of most batholiths must have been of moderate initial thicknesses, to be measured in hundreds or thousands of feet but not in tens of thousands of feet. In one part at least the roof rock of the great Boulder batholith of Montana was about 1000 feet thick.[1] The original cover of the Snoqualmie batholith of Washington is stated to have had locally no greater thickness than 4000 feet.[2]

Notwithstanding the great areas covered by these magmatic bodies, and also in spite of the fact that roof rock is generally denser than acid magma, geologists are agreed that batholithic roofs have generally remained intact during the respective magmatic periods. In fact, the geological text-books make no mention of the possibility

[1] R. W. Stone, Bull. 470, U. S. Geol. Survey, 1911, p. 79; cf. J. Barrell, Prof. Paper No. 57, U. S. Geol. Survey, 1907, p. 166.

[2] G. O. Smith, Snoqualmie folio, U. S. Geol., Survey, 1906, p. 12.

of partial foundering of the roof of a subjacent body, and it is not likely that it has taken place in the case of the great majority of visible stocks and batholiths. Nevertheless, there are evidences that some subjacent masses have been opened to the sky over areas much more extensive than those represented in apophysal dikes.

Scottish geologists have described a case, at Glen Coe, where part of a batholith's roof has sunk along peripheral faults (a "cauldron-subsidence"). As the sinking progressed the magma was squeezed up, following the faults on nearly every side of the sunken area (Fig. 116, p. 197). If the faulting had progressed still further it seems inevitable that foundering would have occurred.[1] The present writer has outlined the facts which suggest that the rhyolite plateau of the Yellowstone National Park represents a broad cicatrix in the roof of a

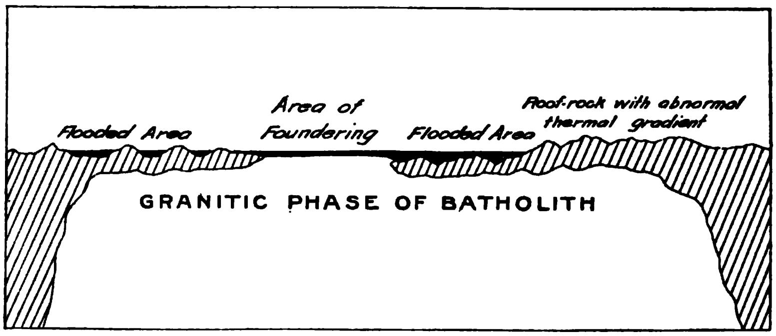


FIG. 71.—Ideal section illustrating the hypothesis that the rhyolite and the thermal phenomena of the Yellowstone Park are directly related to the foundering of part of the roof of a late-Tertiary batholith.

Pliocene batholith; that over hundreds of square miles the batholithic roof was very thin when the rhyolite plateau was formed; and that this thin roof was locally swallowed up (Fig. 71). The field habit and field relations of the rhyolite, and particularly the long persistence of geyser activity on the plateau, are evidences supporting this hypothesis[2] (Fig. 72).

In the basin of the Fox River, Wisconsin, the granite of a pre-Cambrian batholith is gradually transitional, through a massive rhyolite porphyry (keratophrye), into a rhyolite in which all the evidence of former flowage and rapid surface cooling is apparent. The areas of granite are contiguous and the areas of keratophyre lie in a zone bordering the granite on the east and south, while the rhyolite

[1] C. T. Clough, H. B. Maufe, and E. B. Bailey, Quart. Jour. Geol. Soc., Vol. 65, 1909, p. 670.

[2] R. A. Daly, Proc. Amer. Acad. Arts and Sciences, Vol. 47, 1911, p. 63.

areas lie in an outer zone beyond the keratophyre and farthest removed from the granite.[1]

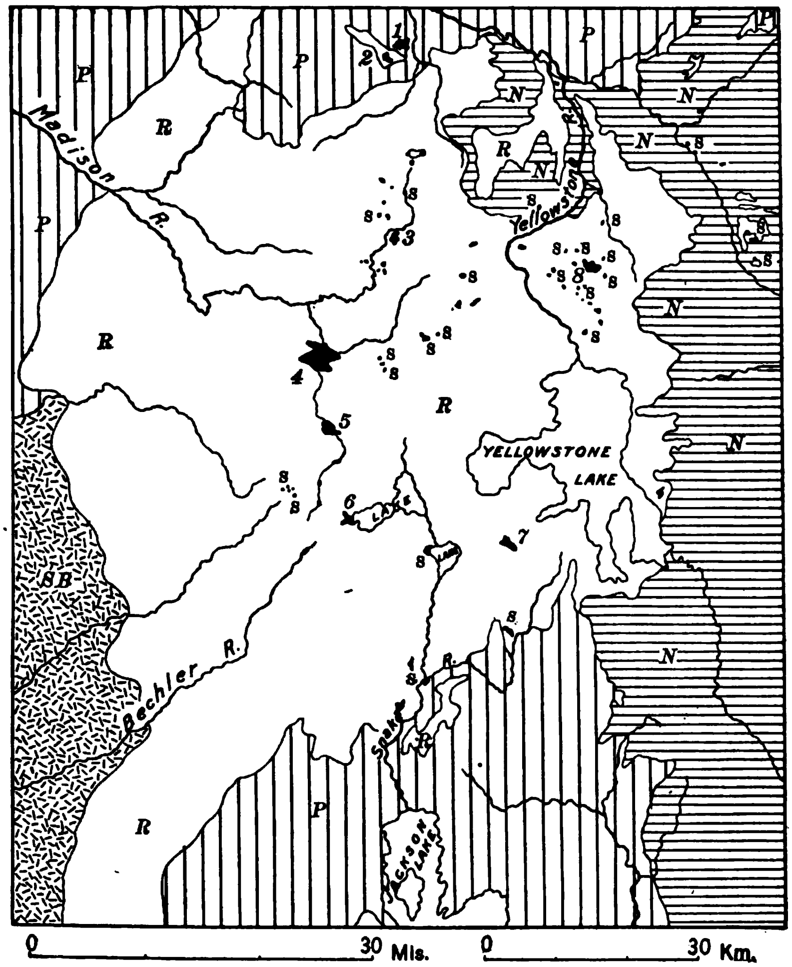


FIG. 72.—Map of the Yellowstone Park, showing the unexampled profusion of hot springs (*S*) and geyser basins. (From Yellowstone National Park Folio, No. 30, U. S. G. S., 1896.) *P*, pre-Tertiary formations; *N*, pre-rhyolite, Neocene volcanic breccias; *R*, rhyolite (Pliocene or Miocene); *SB*, Snake River basalt (Pliocene); *black spots*, sinter deposits. *1*, Mammoth Hot Springs. *2*, Terrace Mountain. *3*, Norris Geyser Basin. *4*, Lower Geyser Basin. *5*, Upper Geyser Basin. *6*, Shoshone Geyser Basin. *7*, Heart Lake Geyser Basin. *8*, Hot Spring Basin.

At several localities in Sweden the acid porphyries (included in the "leptites") seem to pass gradually into granites (also orthogneisses),

[1] W. H. Hobbs and C. K. Leith, Bull. Univ. Wisconsin, No. 158, 1907, p. 266.

which crop out with batholithic proportions. The massive porphyries have the fine grain and other characteristics of more or less metamorphosed extrusive rhyolites. They are often directly associated with tuffs and other pyroclastic beds of the same chemical composition.[1]

The phenomena suggest very strongly that some of the pre-Tertiary batholiths actually reached the earth's surface through orifices vastly larger than ordinary dike fissures. There the magmas were chilled in much the same way as ordinary flows of rhyolite have been chilled. The glassy, scoriaceous, and pyroclastic rocks, however formed, have been greatly deformed and eroded, so that it is difficult to make a final test of this explanation for these older bodies. The case of the Yellowstone rhyolite would doubtless yield more conclusive results in a complete investigation of the problem. Whatever be the fate of the roof-foundering hypothesis, it points to the need of a revision of the conception that all large bodies of granitoid constitution are "plutonic" in origin. It must be remembered that the thin, scoriaceous, glassy, or lithoidal cap, formed by atmospheric chilling in an area of foundering, would be immediately subject to erosion and to ultimate complete removal. It would be very difficult to distinguish such a denuded batholith, of granular texture because cooled slowly beneath the cap, from one which has had a roof of sediment or schist. Roof foundering may, in fact, have occurred much more often than is indicated in the districts so far discussed.

In recognizing this class of truly cicatricial batholiths we have departed from the general plan of classifying igneous bodies on the basis of fairly uniform agreement among geologists as to types of field relations. The departure has been made in the interest of greater completeness for the classification.

III. Central Eruptions

Ordinary volcanoes are characterized by piles of extrusive material which has been accumulated pericentrically. The main gas vent of a volcano is also the main vent for the discharge of rock matter, whether fluent or solid. For this reason the type of extrusion generally most familiar has come to be called "central" eruption.[2] (See Frontispiece.)

The kinds of rock bodies associated with central eruption are

[1] A. G. Högbom, Bull. Geol. Inst. Upsala, Vol. 10, 1910 (reprint), pp. 36, 46, 56. In volume 5 of the same bulletins (1901, p. 19) O. Nordenskjöld notes that the extensive hälleflintas of northeastern Småland are transitional into granites and suggests that they are surface phases of those granites.

[2] A valuable account of central vents is to be found in G. Mercalli's "I Vulcani della Terra," Milan, 1907.

already so familiar to the reader that only a brief description of them is here necessary. They may be listed as follows:

ROCK BODIES

1. Necks.
   a. Tuff necks.
   b. Lava necks.
   c. Composite necks.
2. Plugs, domes (endogenous growths), aiguilles, cumulo-volcanoes, mamelons.
3. Flows; superfluent, interfluent, effluent streams.
   Special phases and features: Block lava, ropy lava, pillow (ellipsoidal) lava, tunnels, lava cascades, lava scarps, tumuli, hornitos.
4. Cones.
   a. Tuff cones, cinder cones, ash cones.
   b. Lava cones.
      (1) Lava domes (exogenous growths).
      (2) Lava rings.
      (3) Driblet cones.
   c. Composite (normal) cones, breached cones.
   d. Cone clusters, cone chains.

The negative topographic forms associated with central eruptions may also be reviewed in summary form, since many of them are connected with the essential mechanism of igneous eruption. The more important forms are as follows:

NEGATIVE RELIEFS (depression forms)

1. Craters.
   a. Lava pits.
   b. Maars (volcanic embryos).
   c. Blow-holes.
   d. Adventive craters (parasitic, lateral).
   e. Nested craters.
2. Calderas (evisceration by explosion).
   a. Simple calderas.
      (1) With lava discharge.
      (2) Without lava discharge.
   b. Nested calderas.
   c. Sunken calderas.
3. Volcanic sinks.
   a. Simple sinks.
   b. Nested sinks.
4. Volcanic rents.

ROCK BODIES

Volcanic Necks.—In many hundreds of cases, secular erosion has removed volcanic cones wholly or in part and has often denuded the non-volcanic formations underlying the cones. The feeding vents have thus become exposed at levels far below the floors of the

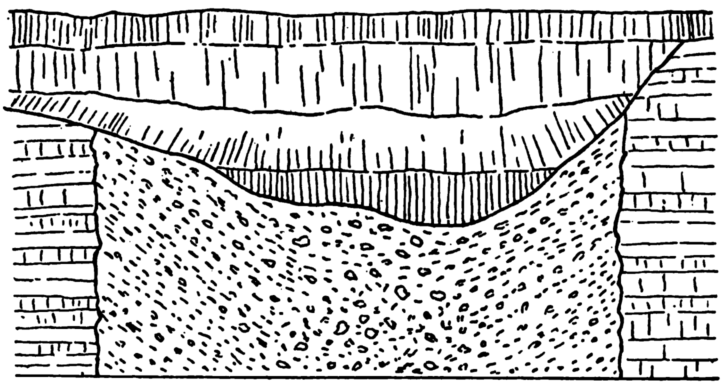


FIG. 73.—Section of volcanic tuff neck piercing and overlain by plateau basalts, Faroe Islands. (After A. Geikie, Ancient Volcanoes of Great Britain, Vol. 2, 1897, p. 295.) Scale, 1:1,300.

craters. The typical vent of the central type is roughly cylindrical or neck-shaped. Even at considerable depth many of the vent fillings or necks are known to be composed wholly of pyroclastic material, with which some of the country rock may be mixed. These are gen-

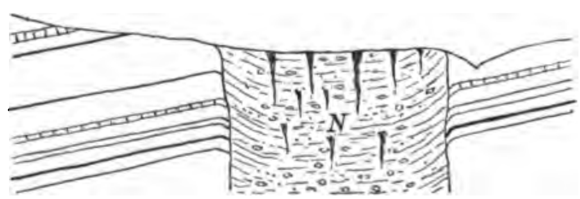


FIG. 74.—Section of Carboniferous neck at East Grange, Perthshire. (After A. Geikie, Ancient Volcanoes of Great Britain, Vol. 1, 1897, p. 426.) The strata traversed are Carboniferous shales, coal, ironstone, and limestone. The neck (*N*) is composed of clays, full of fragments of sandstone, shale, and coal, without igneous rock; was it due to phreatic explosion? The neck is from 1,500 to 2,000 ft. in diameter.

erally called *tuff necks* (Figs. 73–5). Other vents, *lava necks* (Figs. 76 and 136), are filled entirely with massive lava; while still others, *composite necks*, are made up of pyroclastic rock cut by massive lava (Figs. 77–80).

In certain young, though extinct volcanoes, the lava has risen high in the craters, so as to form lava lakes with areas much greater than the average cross-sections of the respective necks. The whole mass may then solidify or part of the lava may sink away (Figs. 81 and 82). In

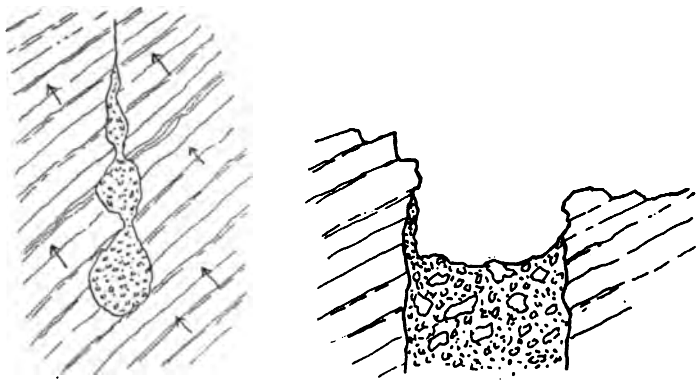


FIG. 75.—Plan and section of explosion fissure east of the Rock and Spindle, Fifeshire. (After A. Geikie, Geology of Eastern Fife, 1902, p. 211.) The breccia is composed of fragments of shale and sandstone. Fissure about 125 ft. long. Arrows show the dip of the strata traversed.

such cases the word "neck" is specially well chosen for the filled pipe joining the "body," the subterranean magma chamber, to the "head," the relatively large prism of lava in the crater. If the erosion surface

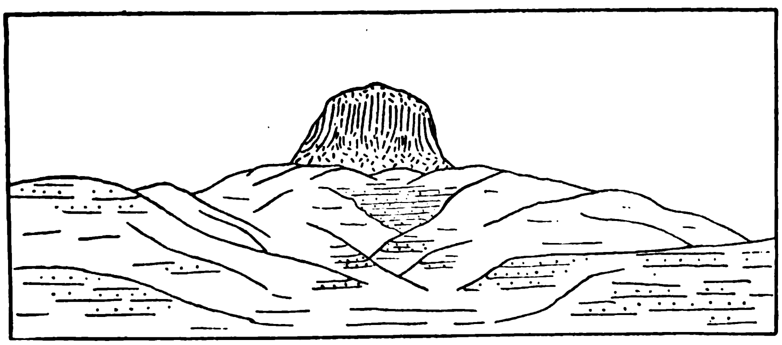


FIG. 76.—Sketch of the Cabezon basaltic neck, New Mexico. (After D. W. Johnson, Bull. Geol. Soc. Amer., Vol. 18, 1907, p. 310.) The neck is about 1,400 ft. in diameter; its summit is 2,160 ft. above the valley.

nowhere cuts under that prism, a mistaken idea is possible as to the order of dimensions for the neck beneath. The vent at Kilauea can hardly have a cross-section of more than 400,000 square feet, and there are reasons for considering it as less than 50,000 square feet. At certain times, by a rise of the lava, the area of the lava lake is as much as 1,500,000 square feet, perhaps fifty or more times the cross-section

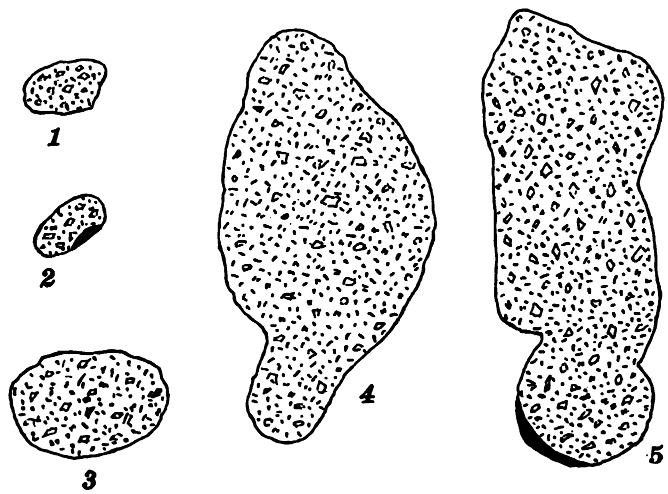


FIG. 77.—Plans of Permian tuff necks, Ayrshire. (After A. Geikie, Ancient Volcanoes of Great Britain, Vol. 2, 1897, p. 64.) Solid black in *2* and *5* represents massive lava. Scale, nearly 1:12,000.

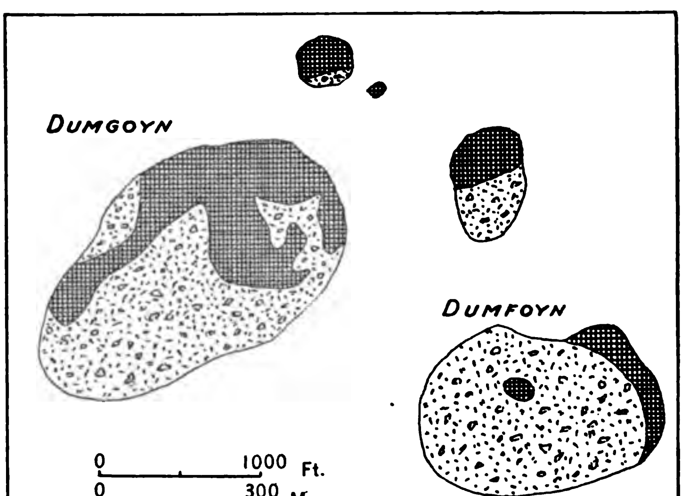


FIG. 78.—Ground plans of composite necks, Stirlingshire. (After A. Geikie, Ancient Volcanoes of Great Britain, Vol. 1, 1897, p. 395.) *Shaded areas*, massive lava; *dotted areas*, tuff and agglomerate.

area of the vent. Similarly, the flaring, superficial portion of a vent may be easily mistaken for a true neck. Often an enormous pit has been developed over a vent by one or more major explosions and then filled with tuff and breccia. Unless denudation has removed the flar-

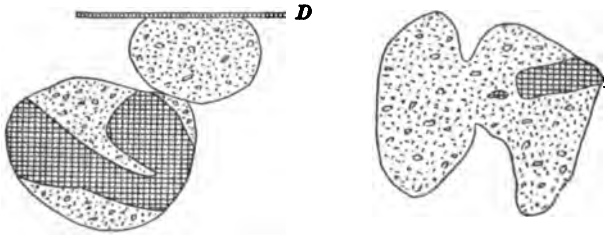


FIG. 79.—Twin volcanic necks of Carboniferous date, Scotland. (After A. Geikie, Ancient Volcanoes of Great Britain, Vol. 1, 1897, p. 396.) *Shaded areas*, massive lava; *dotted areas*, pyroclastic material; *D*, dike. Scale, 1:14,500.

ing part of the pyroclastic deposit, the outcrop of the latter may exceed many times the average cross-section of the vent. It seems likely that some of the recorded tuff "necks" of Scotland and elsewhere are seen

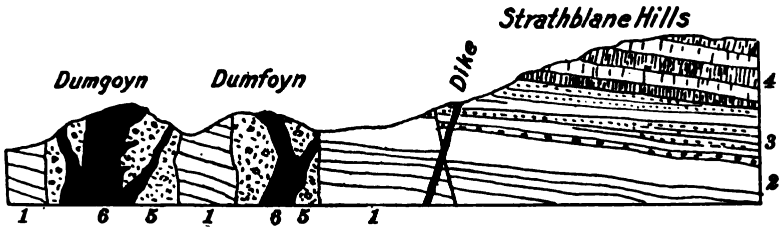


FIG. 80.—Section of composite necks, Stirlingshire. (After A. Geikie, Ancient Volcanoes of Great Britain, Vol. 1, 1897, p. 400.) *1*, *2*, *3*, Paleozoic sediments; *4*, andesitic lava; *5*, agglomerate; *6*, diabase. Scale, 1:16,000.

in the outcrop only at sections passing through the upper flaring portion of the pyroclastic filling.

In any case, central vents are always small, even minute, when com-

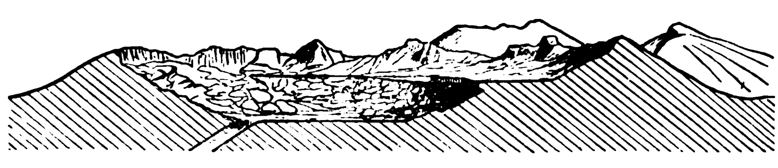


FIG. 81.—Volcanic vent and crater, Ice Spring cluster, Utah. (After G. K. Gilbert, Rep. Surveys West of 100th Meridian, 1875, p. 139.) Note eccentric position and oblique attitude of the vent, and the shelf of congealed lava. The crater is about 600 ft. wide at its outer lip.

pared with the sections of the larger intrusive bodies. The accompanying table shows the range of diameters in many typical necks.

TYPICAL SIZES OF VOLCANIC NECKS

Region	Number of necks	Range of diameters: Feet	Range of diameters: Meters
Cape Province, South Africa:			
Namqualand	16	135–2250	40–680
Wodehouse district	15	.....	.....
Barkly East district	20	.....	.....
Elliot district	17	12–5280	4–1600
Herschel district	22	.....	.....
Matatiele district	19	.....	.....
Maclear	15	120–5280	36–1600
Eastern Fife, Scotland	80	30–5280	9–1600
Ayrshire, Scotland	60	60–4000	18–1200
Swabia	132	.....	.....
New Mexico	"several hundreds"	1400, largest described	Up to 420
Leucite Hills, Wyoming	6	120–500	36–150

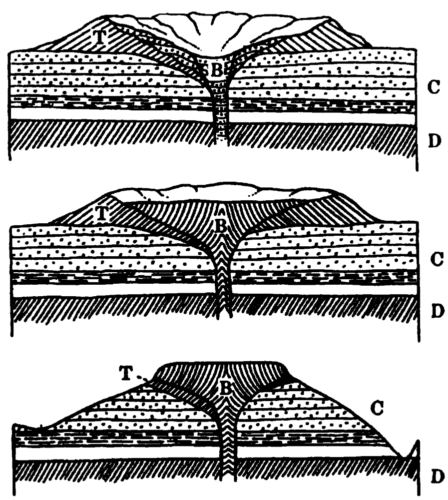


FIG. 82.—Sections showing erosion of crater charged with congealed lava. (After H. Laspeyres, Das Siebengebirge am Rhein, 1901, pp. 118–9.) *D*, Devonian formation; *C*, trachyte tuff; *T*, basaltic tuff; *B*, massive basalt. The upper section illustrates a maar-like crater; the middle section, a lava lake; the lower section, a lava mesa left after prolonged erosion (Kuppe).

Volcanic Plugs.—Lacroix, Heilprin, Hovey, Jaggar, and others have made the "dome," "spine," or "aiguille" of Mont Pelée so famous, and have illustrated it so bountifully that a detailed account of this marvellous body is not here necessary (Figs. 83 and 84). Its upthrusting in 1902 has stimulated search for volcanic masses formed by similar mechanism. Various authors have suggested parallels among the extinct volcanoes.

Jaggar has observed the upthrusting of a "dome" of the Peléan type at Bogoslof (Fig. 85). The new dome at Tarumai, Japan, is illustrated in Fig. 86.

In exceptional cases the highly viscous lava of relatively cool vents has exuded in quantity sufficient to form distinct domes at the surface, covering and notably overlapping the limits of the vents (cumulo-volcanoes, mamelons). These domes have grown *endogen-*

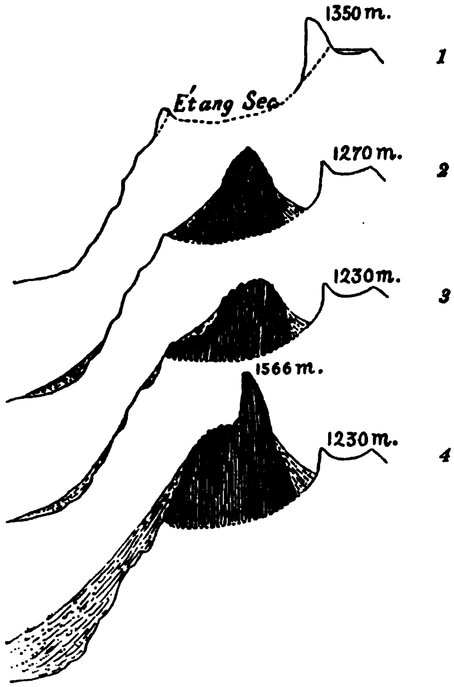


FIG. 83.—Sections showing four stages in the recent history of Mt. Pelée (After A. Lacroix, La Montagne Pelée et ses eruptions, 1904, p. 121.) *1*, The summit before the great eruption of 1902. *2*, The spine on July 31, 1902. *3*, The spine on Oct. 4, 1902. *4*, the spine on Mar. 9, 1903.

ously, as bodies of unbroken, massive lava. A classic example is that of the trachytic Grand Puy of Sarcoui in the Auvergne.

Lava Flows.—The usual massive components of a central volcano are, of course, flows. Dana has described these as *superfluent*, *effluent*, or *interfluent*, according to the mode of discharge, which is respectively at the summit of the volcano, at a lateral fissure, or by way of subsurface cavities within the cone.[1]

Certain details of individual lava flows have received special names

[1] J. D. Dana, Characteristics of Volcanoes, New York, 1891, p. 2.

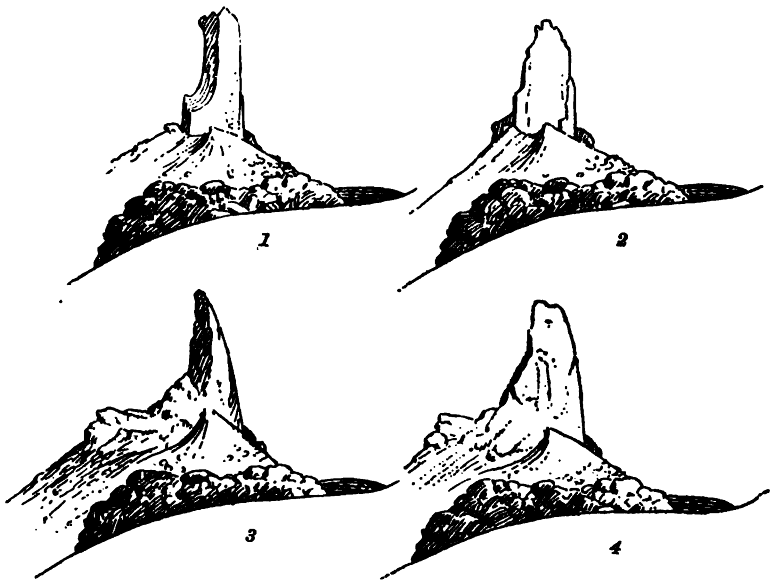


FIG. 84.—Sketches of the Mt. Pelée spine, showing its changes. (After A. Lacroix, La Montagne Pelée et ses eruptions, 1904, pp. 124, 126, 127.) *1*, Nov. 22, 1902. *2*, Nov. 25, 1902. *3*, Apr. 3, 1903. *4*, June 13, 1903. The respective heights of the summit were: 1,566, 1,548, 1,593, and 1,582 meters. The elevation of the crater rim (right) is 1,264 meters.

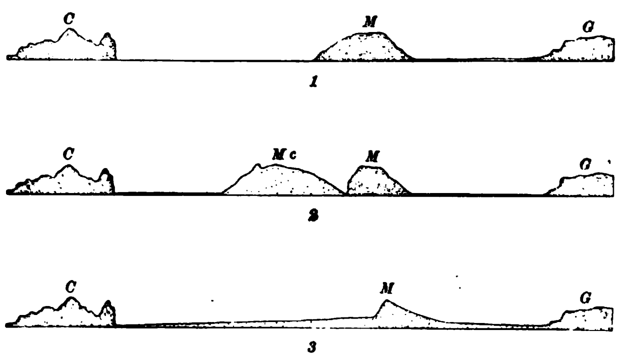


FIG. 85.—Sketch profiles (partly diagrammatic) showing changes in the Bogoslof Islands in 13 months. (After T. A. Jaggar, Bull. Amer. Geog. Soc., Vol. 40, 1908.) *1*, September, 1906. *2*, Aug. 7, 1907. *3*, Oct. 15, 1907. *C*, Castle Rock (Bogoslof); *G*, Grewingk; *M*, Metcalf cone; *Mc*, McCulloch cone, a temporary plug-dome of andesitic composition. After the rising of McCulloch dome a major explosion destroyed it and part of the older Metcalf cone.

and represent features needing explanation by a complete theory of igneous action. The more striking items may be mentioned.

Block lava, forming the *aa* fields of Hawaii, *les cheires* of France, and the Malpais of Mexico, needs no formal description in this place. Similarly, *ropy lava* (*pahoehoe, Fladenlava, Plattenlava*), *pillow lava*,

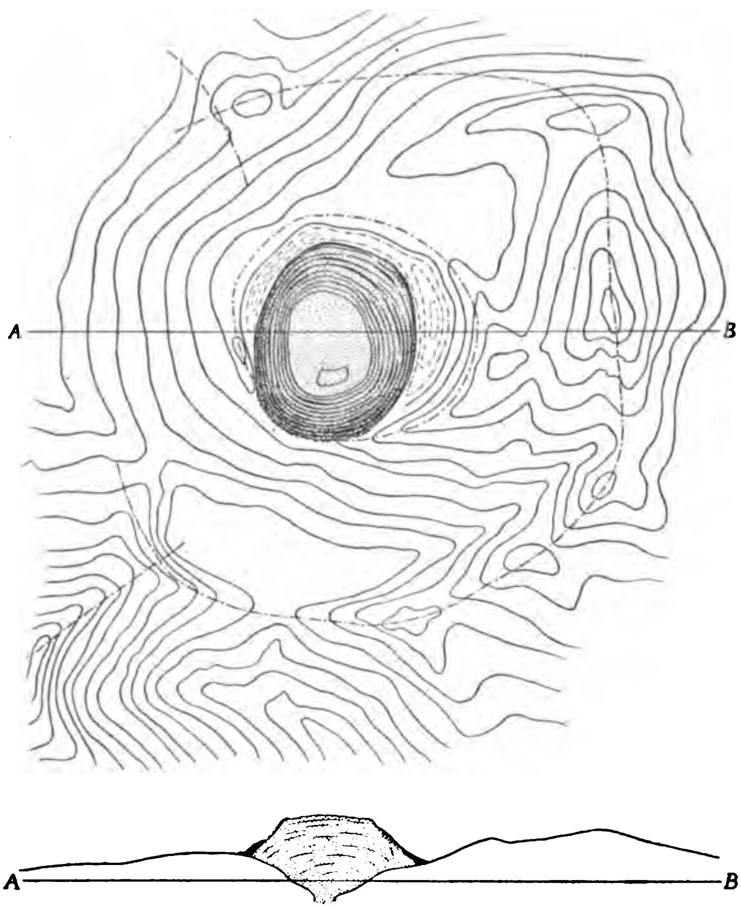


FIG. 86.—Map and section of the new plug-dome (*dotted*) at Tarumai, Japan. (After H. Simotomai, Zeit. Ges. Erdkunde, Berlin, 1912, p. 433.) Top of dome about 1,000 meters above sea; contour interval, 10 meters. Scale, 1:20,000.

and such topographic features as constructional *lava scarps*, *lava cascades*, and *lava tunnels* are too familiar to need comment.

Many congealed flows of the pahoehoe type exhibit swellings or low domical hills from 10 to 20 or more meters in length and a few meters in height (Fig. 87). These may be called *tumuli* (*Schollendome* of

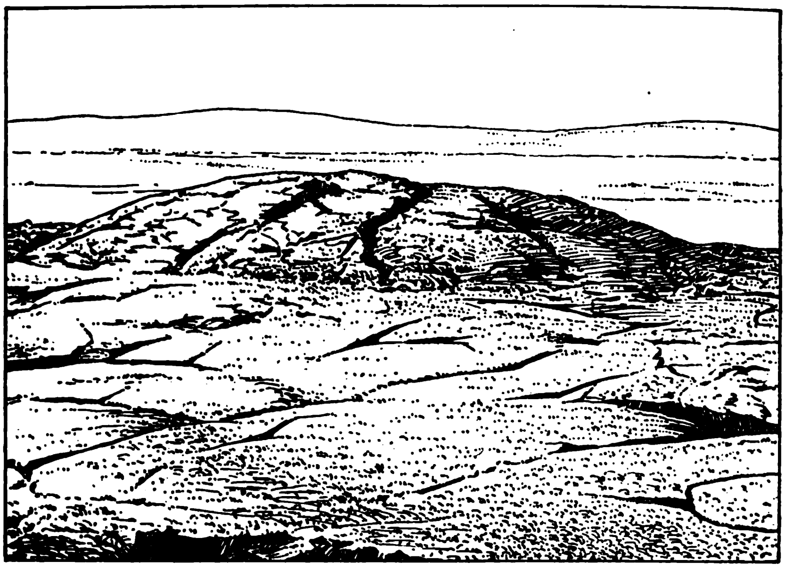


FIG. 87.—A tumulus in the floor of the Kilauean sink, Hawaii. (From a photograph by I. Friedlaender, pub. in G. Mercalli's I Vulcani Attivi della Terra, 1907, p. 51.)

FIG. 88.—A tumulus in the floor of Kilauea. (From a photograph by the author, 1909.) During the updoming, liquid lava issued from the cracks characteristic of this volcanic form.

Friedlaender). Hundreds are to be seen in the lava fields of Hawaii. They are to be explained by the local hydrostatic pressure of still fluid lava beneath the already chilled crust of a somewhat inclined flow. The ropy crust is characteristically fractured by the pressure and sometimes the liquid lava escapes through the fractures (Fig. 88). The intumescence is analogous to the deformation of a laccolith's roof.

A *hornito* is a gas-emitting vent on, and originating in, a lava flow. The writer has not been able to find in volcanic literature a clean-cut definition of this term, but, by usage, it seems to include vents which have built up driblet cones as well as those developing minute cones of ash or tuff on the back of the parent flow. Pacheco has recently figured examples in the Canary Islands.[1]

Volcanic cones themselves hardly need detailed consideration in a scheme for their classification as bodies of igneous rock. As with necks, the basis for division here chosen is the relative importance of pyroclastic and flow in each cone. Dikes, sheets, and sometimes laccoliths, cut the extrusive rocks of most of the greater cones but such material is usually too insignificant to affect the essential form and contents of a cone.

TUFF CONES, otherwise called cinder cones or ash cones, are, when ideally developed, always small.

LAVA CONES, those composed wholly of lava flows, are relatively rare. An appreciable proportion of pyroclastic material is generally interbedded with the dominant massive rocks of this class of extrusive bodies.

A pure type is the *driblet cone,* found in Hawaii, in Réunion, and in other basaltic fields (Fig. 89).

Lava rings are the greater driblet cones formed by the symmetrical upbuilding of the walls of a lava lake by the congealing of intermittent thin overflows of the lake. In 1893 such a self-built rim was to be seen around the Kilauean lake.[2] A good example was found by the present writer on Mount Hualalai (Hawaii) southeast of its summit.

Lava domes are the greater masses of lava, which, in the form of many individual flows, have issued from central vents in the proper abundance and proper directions to build a dome-shaped pile of lava. Apparently in all cases some subordinate intercalations of tuff or breccia are to be found in the actual domes. The world type is Mauna Loa. Excellent examples have been described by Thoroddsen and others

[1] E. H. Pacheco, Mem. R. Soc. Española Historia Natural., Vol. 6, 1910, p. 251.

[2] For admirable illustration see W. T. Brigham's "The Volcanoes of Kilauea and Mauna Loa of the Island of Hawaii," Honolulu, 1909, Plate 50.

in Iceland. Such bodies are of *exogenous* growth and are thus contrasted genetically as well as in size with the plug-domes previously mentioned.

Huge as a lava dome may be, its constituent flows are always, so far as known, of quite moderate individual thicknesses. One of the most favorable sections for observing this fact is the great scarp (according to Lindgren, a fault-scarp) limiting the island of Molokai on the north. There the writer has counted more than one hundred flows in a part of the cliff where it is about 2000 feet in height. The average thickness of the flows is, therefore, not far from 20 feet. The average thickness of the flows in the 2000-foot cliffs of the Haleakala

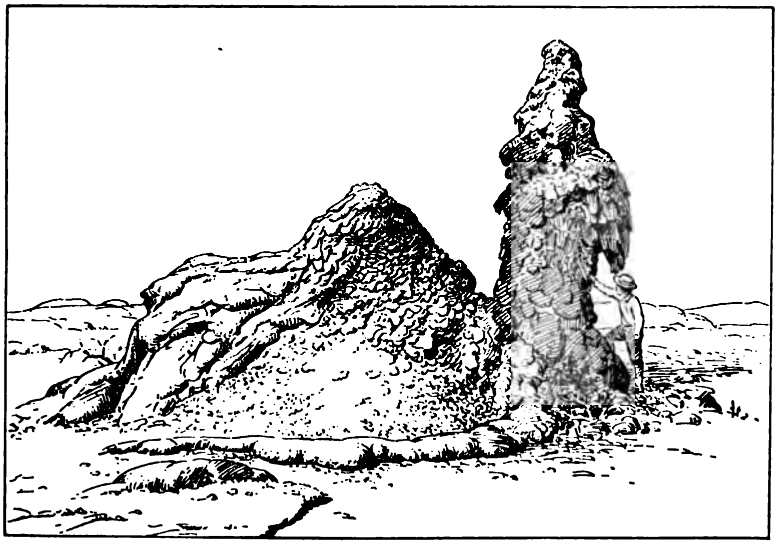


FIG. 89.—Driblet cone near the Kamakaaia cones, Hawaii. (From a photograph by H. E. Wilson, July 14, 1911.)

rent in Maui is nearly similar. Nowhere on Hawaii are the exposures so favorable as in Maui and Molokai, but in the cliffs studied by the writer the flows of Hawaii are probably less than 25 feet in mean thickness. The section in the great canyons of Kauai show the average thickness of the flows to be again of that order.

It appears, then, that the flows of the greater lava domes have average thicknesses much like those observed in the greater fissure eruptions (lava plateaus) of the world; in both cases the lava is generally a typical basalt. (See pages 119–120.)

COMPOSITE CONES, "normal" cones, or cones of the "mixed" type are, of course, the most abundant, including the celebrated living

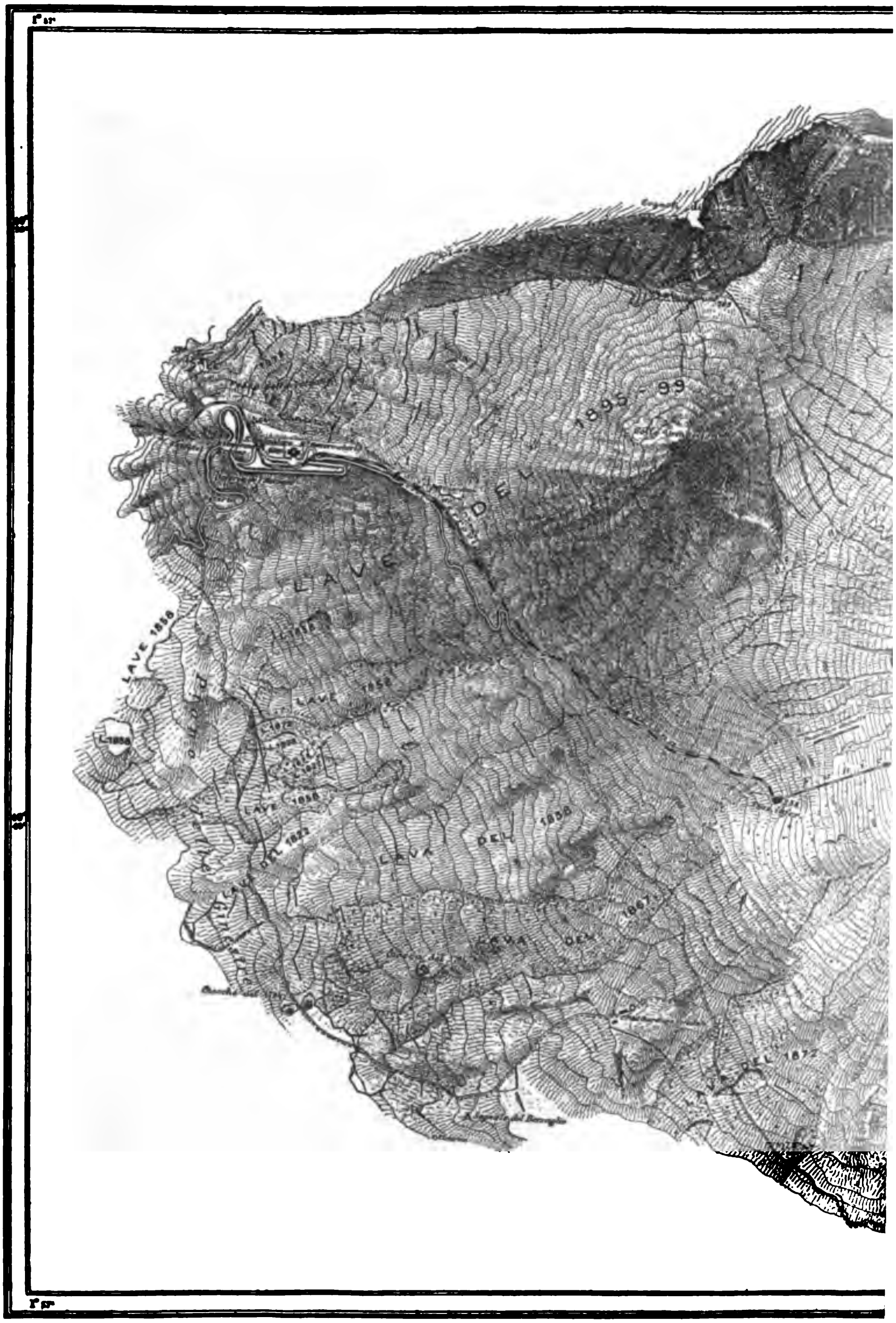
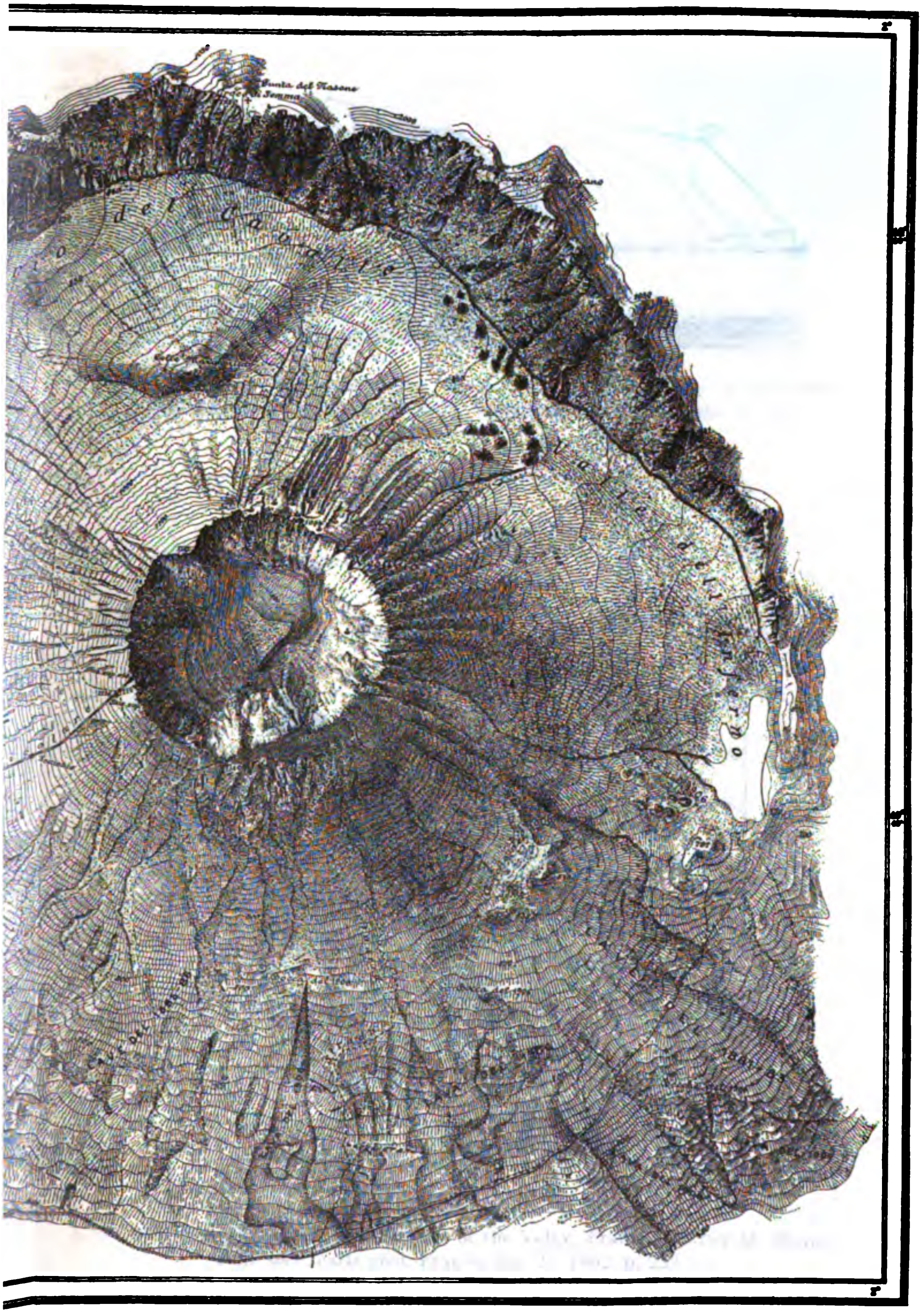


Plate II.—The Cone and Crater of Vesuvius and th
I. Friedlaender, Petermann's Geog. Mitteilung



THE CALDERA WALL OF SOMMA (AFTER A. CASTIGLIONE AND
NGEN, J. PERTHES, GOTHA, 1912). SCALE—1 : 21,800.

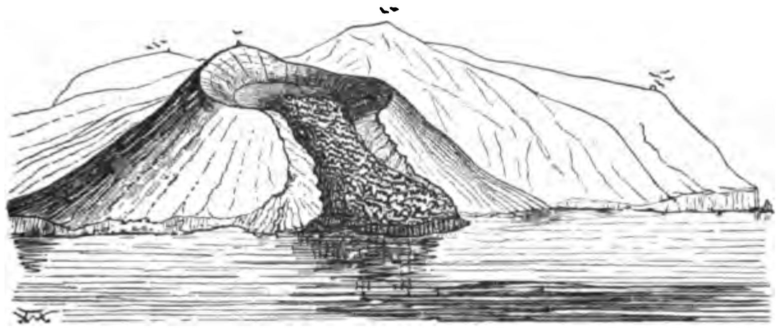


FIG. 90.—Pumice-cone breached by the outflow of an obsidian lava-current, Island of Lipari. (After J. W. Judd, Volcanoes, New York, 1881, p. 124.)

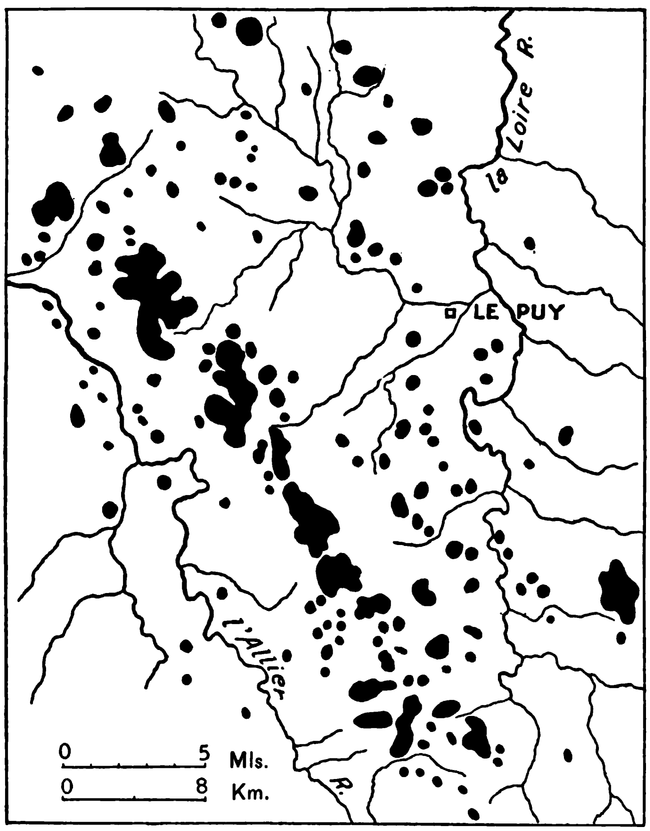


FIG. 91.—Cone chain and cone clusters of the Velay, France. (After M. Boule, Bull. serv. carte géol. France, No. 28, 1892, p. 223.)

volcanoes of the Mediterranean, of Mexico, of Java, etc., and the majority of bodies centrally erupted through geological time (Figs. 171, 186, 191, and Plate II).

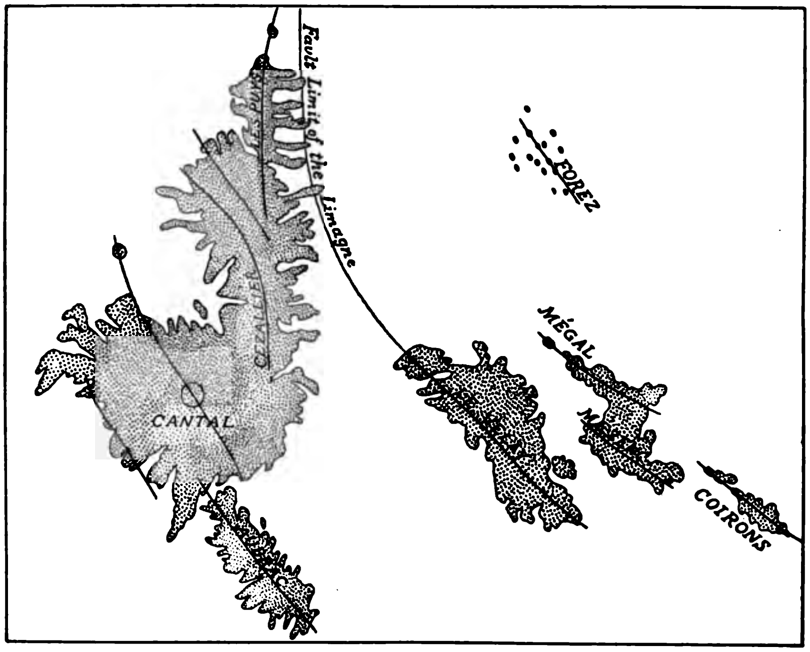


FIG. 92.—Map showing relation of Tertiary volcanoes (*dotted*) of central France to crust fractures. (After Le Service Géologique de la France.) Scale, 1:2,000,000.

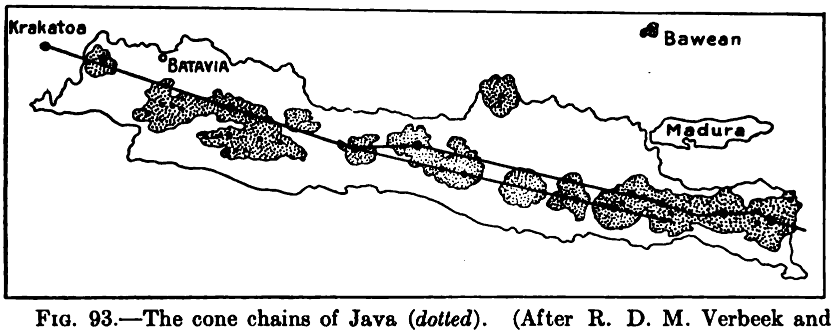


FIG. 93.—The cone chains of Java (*dotted*). (After R. D. M. Verbeek and R. Fennema, Description géol. de Java et Madoura, 1896.) Heavy black dots represent principal vents. Scale, 1:10,000,000.

"Many cones formed in the first instance of scoriæ, tuff, and pumice may give rise to streams of lava, before the vent which they surround sinks into a state of quiescence. In these cases, the liquid lava in the vent gives forth such quantities of steam that masses of froth or scoriæ are formed, which are ejected and accumulate around the orifice. When the force of the explosive action is exhausted, the lava rises bodily in the crater, which is more or less completely filled. But, eventually, the weaker side of the crater-wall yields beneath the pressure of the liquid mass, and this part of the crater and cone

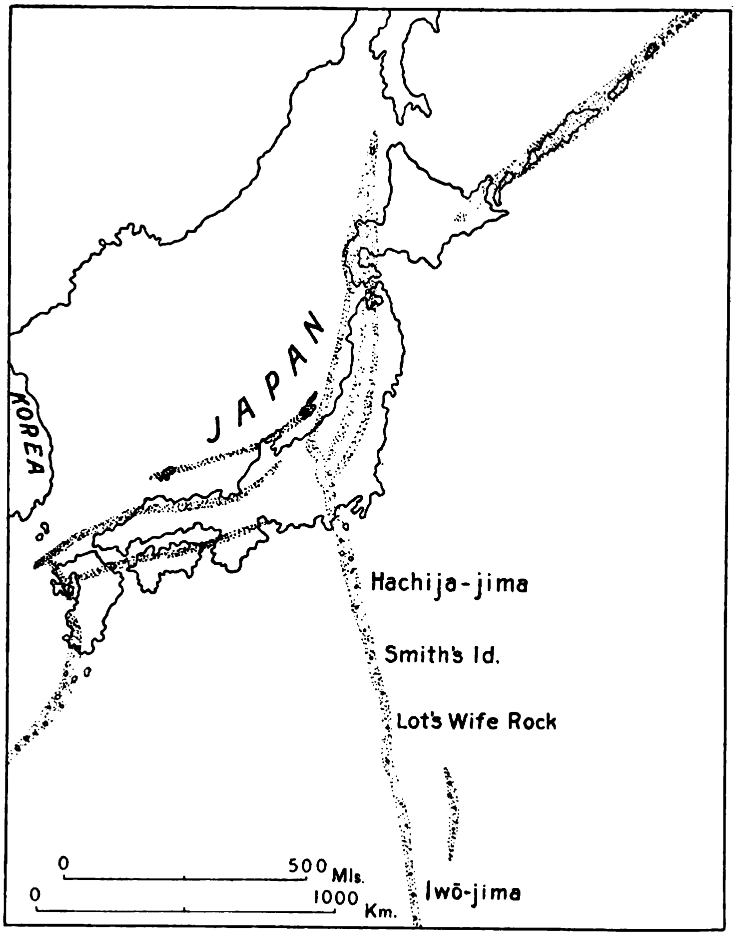


FIG. 94.—The neo-volcanic cone chains of Japan (*dotted*). (After S. Yoshiwara, Geol. Mag., Vol. 9, 1902, p. 298.)

is swept away before the advancing lava-stream. Examples of such '*breached cones*' abound in Auvergne and many other volcanic districts. A beautiful example of a cone formed of pumice, which has been breached by the outflow of a lava-stream of obsidian, occurs in the Lipari Islands, at the Rocche Rosse. It is this locality which supplies the whole world with pumice"[1] (Fig. 90).

[1] J. W. Judd, Volcanoes (International Scientific Series), New York, 1881, p. 123.

Finally, colossal masses of igneous rock are represented in CLUSTERS and CHAINS of cones (Figs. 91, 92, 93, 94). This grouping of units obviously represents one of the chief genetic problems of the igneous rocks.

DEPRESSION FORMS

For the proper understanding and illustrating of the processes by which the extrusive bodies are formed, it is necessary to have in mind the chief topographic forms associated with these bodies. Although a great literature concerning the negative reliefs of volcanic origin has been developed, there is little agreement as to fundamental definitions. In standard works the term "crater" has been applied to genetically quite distinct things, and the name "caldera" has become, through conflicts of definition, much impaired as an aid to rigorous discussion. Failing the authority of a general systematic usage, the writer has selected certain elements in existing definitions and has

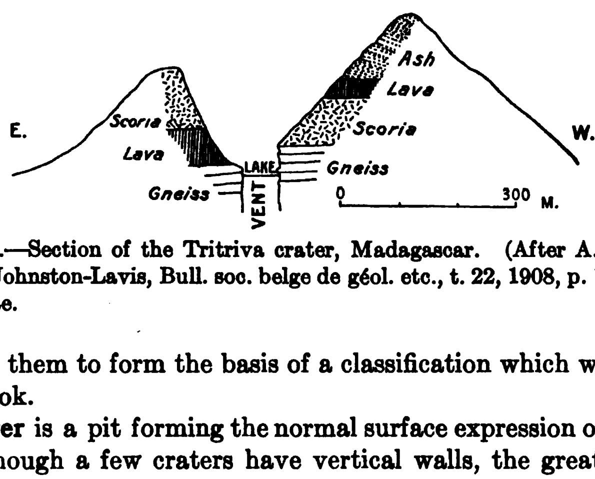


FIG. 95.—Section of the Tritriva crater, Madagascar. (After A. Bourdariat and H. J. Johnston-Lavis, Bull. soc. belge de géol. etc., t. 22, 1908, p. 107.) Scale approximate.

combined them to form the basis of a classification which will be used in this book.

A **crater** is a pit forming the normal surface expression of a central vent. Though a few craters have vertical walls, the great majority have flaring walls (Plate II). The flaring is usually continuous but in some craters the flare is interrupted by subordinate, vertical cliffs overlooking the center of the depression. Under conditions of normal activity, the flat floor of the crater (liquid, pasty, or solid lava) is nearly equal in area to the cross-section of the neck beneath (Fig. 95).

The flare of a crater is produced in three ways: by explosion, by slumping, or by melting of the wall rocks. All three methods are often combined in action. In normal activity the gases producing explosion are chiefly contained in the vent (neck) itself and the figure typically produced by their explosion is an inverted cone. Under the conditions, the floor of the depression can differ little in area from that of the cross-section of the vent beneath. Subsequent slumping of the more or less shattered walls will tend to increase the flare while diminishing, for a time at least, the exposed area of the lava column. Renewed explosion may clear out such débris and restore the typical relation of floor area to the size of the vent. The terraced craters are best displayed in the non-explosive, basaltic volcanoes like the Hawaiian Kilauea, Mokuaweoweo (Mauna Loa), Hualalai, etc. In these cases the flare is produced by the undermining and slow action of the lava lakes, which are intermittently formed in each crater by flooding through the vent (Figs. 81 and 131). During the life time of each lake, the solid rock of its shores is softened and weakened at the contact of the liquid lava, causing rock falls by a kind of lateral stoping. Yet, even in this type the crater is normally floored with liquid or solid lava, whose area is quite moderate and not much larger than that of the cross-section of the feeding vent.

When first formed, a crater may be fissure-like but, as a product of the same mechanism that keeps it open (explosion, slumping, or melting), the ground plan soon becomes subcircular.

Craters, as above defined, have apertures always of small absolute size. The visible, because eroded, rock-filled vents of central eruptions are seldom, if ever, more than 1000 feet in diameter; generally the diameters are much smaller. Observations on hundreds of the intact explosion vents show that no explosion of the directly magmatic gases has cleared the volcanic throats to depths greater than a few thousand feet; rarely is the depth of the visible explosion pit more than 1000 feet. The conical, pure-explosion figure must, therefore, always have moderate dimensions, including the area of the aperture. The aperture is regularly enlarged by slumping but, since the angle of rest for tuffaceous material is nearly thirty degrees, this enlargement is quite limited.

Again, the flare produced by undermining and melting by the lava lake in a crater must be restricted by the size of the lake. On account of the high rate of heat radiation from hot lava, only a small lake is possible at any crater which communicates with the earth's interior through ordinary necks. Limited as the flare so caused must be, it cannot be much enlarged by slumping subsequent to the freezing of the lake or to its diminution of surface through withdrawal of the lava into the vent.

There are, thus, good grounds for including in the conception of a true crater the idea of relatively small size.

Lava pits are those craters which are visibly floored with massive lava, either liquid or solid. The famous pits of Hawaii are illustrated

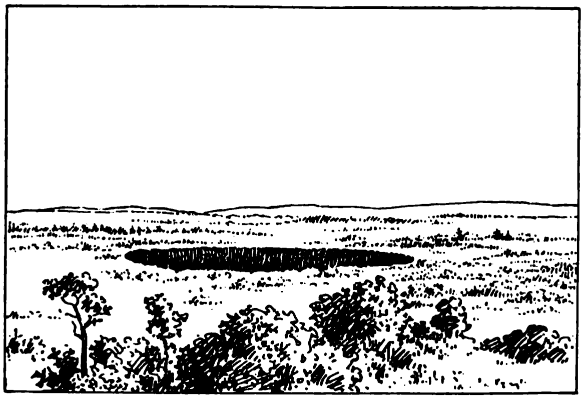


FIG. 96.—Distant view of a small pit crater in the Puna district, Hawaii. (From a photograph by the author, 1909.) The well-like crater is about 200 ft. in diameter.

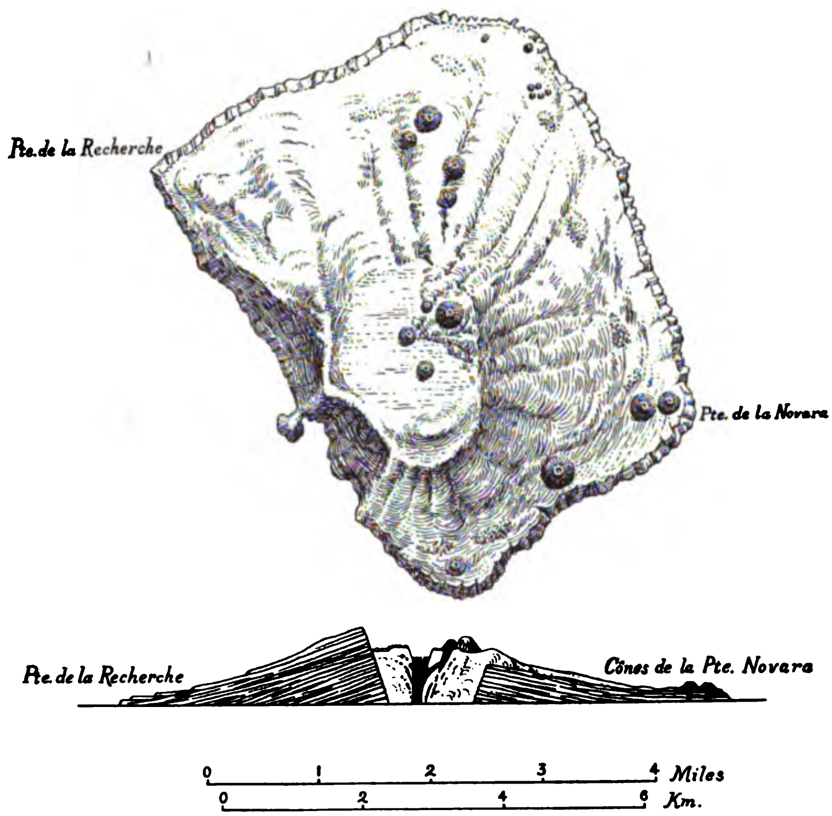


FIG. 97.—Map and section of Amsterdam Island volcano, showing adventive cones and craters. (After C. Vélain, Mission de l'île Saint Paul, 1880, Pl. 26.)

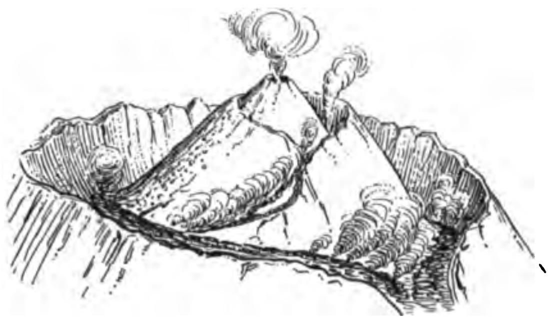


FIG. 98.—The nested craters of Vesuvius, from a sketch by Sir W. Hamilton. (Campi Phlegræi, 1799.)

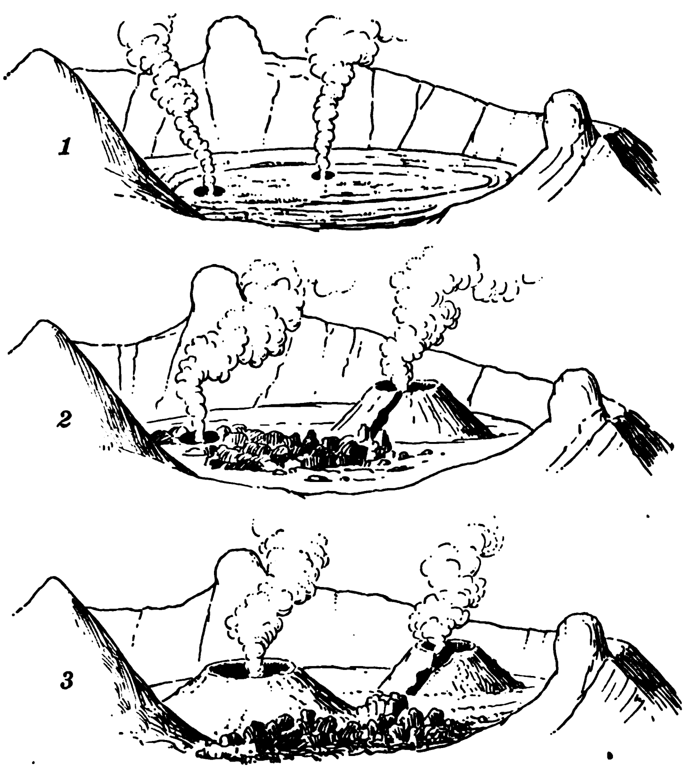


FIG. 99.—Nested craters of Etna in the early part of the 19th century. (After W. S. von Waltershausen, Der Ætna, Vol. 2, 1880, p. 304.) Three stages of the summit crater: *1*, years 1804–5; *2*, years 1805–9; *3*, years 1810–16.

in Figs. 96 and 142. These craters are specially instructive as they have clearly been formed in an older lava plateau, not by explosion but by melting perforation.

Maars are relatively flat-floored explosion craters at vents which are either coneless or else provided with inconspicuous cones. In this class come most of the famous Vulkan-Embryonen, described by Branco in Swabia,[1] (Fig. 144).

Blow-holes are the minute craters formed on the surfaces of thick lava flows. They are often visible on driblet cones.

Adventive (parasitic or lateral) *craters* are those opened on the flanks of great cones (Fig. 97).

Nested craters.—Sometimes central vents show the phenomenon of crater in crater. The smaller crater in each case has evidently been produced by a temporary or permanent restriction of the amount of heat transferred to the vent from the earth's interior, whereby the cross-section of the feeding pipe has been diminished. (For illustrations see Figs. 98 and 99.)[2]

Calderas.—Few terms in igneous geology have occasioned more diversity of definition than the name "caldera." All writers on the caldera agree as to its amphitheatral or circus shape and as to the necessity of considerable size. Beyond those points the various suggestions concerning the proper meaning of the word sharply diverge.

(1) Some authors have used the term as signifying merely a gigantic explosion crater.

(2) Others add to that genetic feature the necessity of a large lateral opening in the wall of the depression, as in the famous Caldera of La Palma of the Canary Islands. This lateral opening should, by this definition, pass into a "barranco" or deep ravine running outward from the volcanic center.

(3) A third group of writers have followed Dutton in defining a caldera as a down-faulted, steep-walled depression formed as a result of volcanic action.

(4) Still others have considered a caldera as chiefly formed by erosion, which has greatly enlarged a normal crater, thus recognizing the co-operation of two genetic conditions.

(5) Finally, Gagel has recently made an exhaustive study of La

[1] W. Branco, Schwaben's 125 Vulkan-Embryonen und deren tufferfüllte Ausbruchsröhren—das grösste Gebiet ehemaliger Maare auf der Erde, Tübingen, 1894. For illustrations of the Eifel maars see R. Lepsius, Geologie von Deutschland, Stuttgart, 1er Teil, 1887–92, p. 333.

[2] Also R. D. M. Verbeek and R. Fennema, Description géologique de Java et Madoura, Amsterdam, Atlas Bijlage 18, Fig. 71; H. Abich, Erläuternde Abbildungen geologischer Erscheinungen beobachtet am Vesuv und Ætna, Berlin, 1837, Plates I and II (Vesuvius in July, 1834, and Etna in June, 1834.)

Palma caldera and has defined the word without any necessary reference to volcanic action. He thinks it advisable to regard these circus-shaped depressions as essentially due to head-water erosion of streams. He even placed in the class of calderas certain amphitheaters which have been eroded out of horizontal sandstones in New South Wales.

Much of the difficulty in reaching a common understanding in this matter is due to the somewhat peculiar conditions at the "Caldera" of La Palma. So many different origins have been assigned to it that an unprejudiced person may feel no compulsion in settling on the essential elements, either of form or of genesis, in this one case. Lyell, himself, who made this depression famous during his discussion of von Buch's elevation theory of volcanoes, could not decide as to its mode of origin, but he called the great pit of Mt. Somma (the atrio) a caldera, while recognizing that it was formed by explosion. In 1860 Hartung described the "Caldeira das Sete Cidades," the "Caldeira de Santa Barbara," and three other named "caldeiras" of the Azores, as due to repeated volcanic explosions.[1] These and other writers helped to establish the tradition that a caldera is to be regarded as a gigantic explosion form, either with or without a lateral opening or barranco.

It is also true that the Portuguese use the word "caldeira," not only for depression of explosion, but also with the meaning of "boiling springs," as in "Caldeiras das Furnas" of the Azores (Hartung). Thus, as a common noun, the Latin peoples use the word in totally different senses; always a "caldron" or "kettle," but now almost literally, and again in a remotely figurative sense. Accordingly, there is no antecedent, formal objection to introducing the word into technical geology with a figurative meaning. The one indispensable condition is that it shall have a definite meaning. Now that there is pressing need for a term for the greater explosion depressions in volcanic regions, geology will certainly follow the line of least resistance in adhering to the definition implied in the use of Lyell, Hartung, and other of the older writers. The "caldera" of Dutton may be called a "volcanic sink," as noted below. The erosion "Kessel" of Gagel, if named specifically from a locality type, should be referred to a type much less subject to difference of interpretation than the Caldera of La Palma.

Regarding calderas as explosion forms, it remains to distinguish them from ordinary explosion craters. As the word "caldera" has been used, it has almost always referred to very large depressions. If these are correctly interpreted as due to major explosions, they cannot

[1] G. Hartung, Die Azoren, Leipsig, 1860, pp. 311–312.

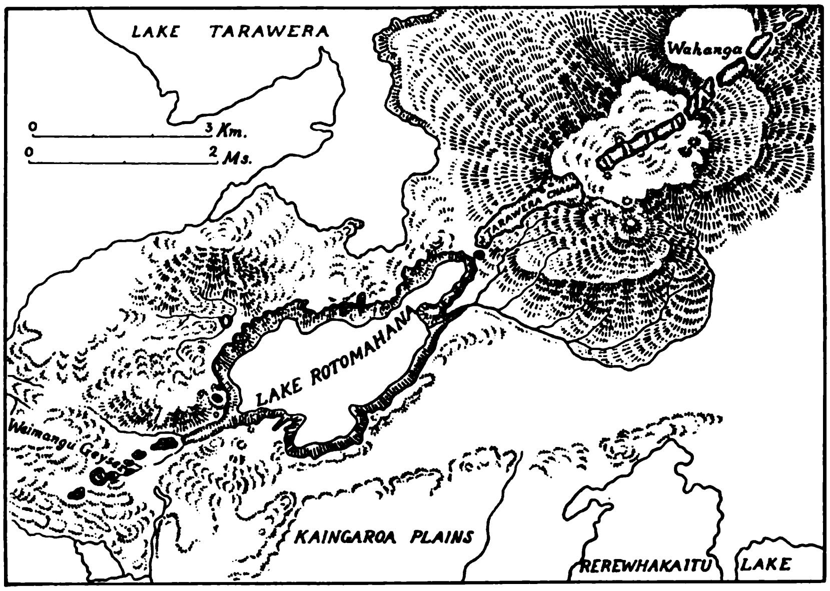


FIG. 100.—The Tarawera rift and Rotomahana caldera, New Zealand. (After A. P. W. Thomas, whose map is reproduced by J. M. Bell, Geog. Jour., 1906.)

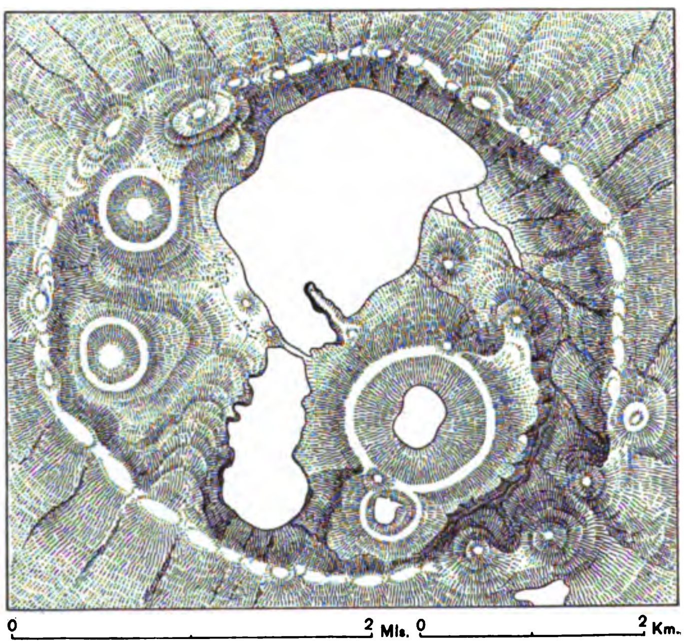


FIG. 101.—Map of the Caldeira of the Sete Cidades, San Miguel Island, Azores. (After G. Hartung, Die Azoren, 1860, atlas.) Several young craters are nested in the caldera.

safely be described as "craters" in the sense above given to that word. If the actually exposed "necks" of the world indicate the maximum size of central conduits, the vents beneath calderas must have cross-sections much smaller in area than the floors of the corresponding great depressions. The writer is, in fact, inclined to make this the criterion for distinguishing explosion craters from calderas. In each of the latter the area of the floor is many times greater than the cross-section of the magmatic column exposed to the air by the explosion.

Illustrations of *simple calderas*, in the sense here used, are given in Figs. 100 and 101.

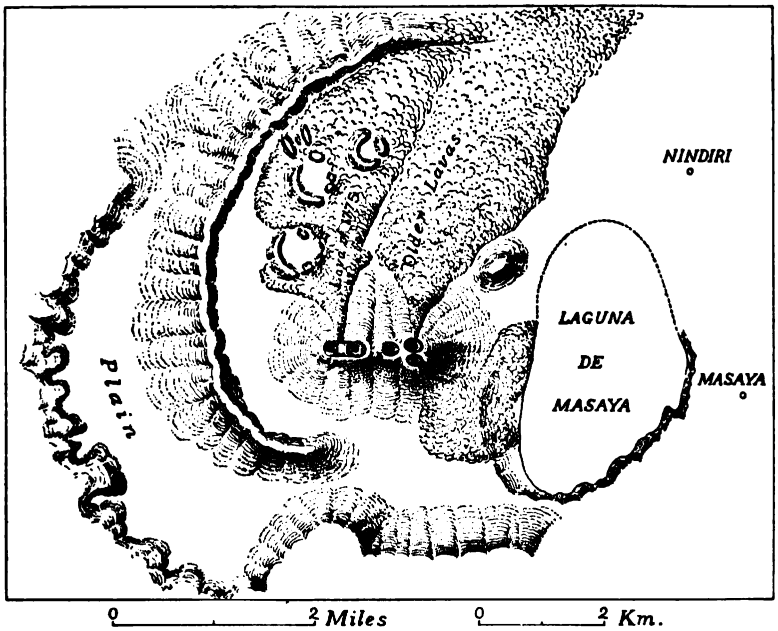


FIG. 102.—Nested calderas at the Masaya volcanoes, Nicaragua. (After K. von Seebach, Abhand. k. Ges. Wiss. Göttingen, Phys. Kl., Vol. 38, 1892, p. 58 and Taf. 9.) The outer escarpment is the eroded lip of the older caldera. Within it is seen part of the younger caldera ring, within which are nested the active Nindiri-Masaya cones.

If the genesis of these depressions has been correctly stated, there can be little doubt as to the necessity of distinguishing them from true explosion craters, for it is scarcely credible that such relatively vast hollows represent the figures due merely to the explosion of gases within columns of liquid magma. An extreme case is represented in the summit caldera of Bandai-San, in Japan (1888), which is said to have been formed by a prodigious explosion, without the exposure of any liquid magma whatever.[1] The proposed distinction between "craters" and "calderas" thus suggests a genetic distinction between the two classes of forms. It is hardly necessary to add that the assignment of a small explosion depression to the class of craters or to the class of calderas, as here defined, may occasionally be very difficult, if not impossible; but such a trouble cannot outweigh the advantage of having systematic designations for the types which can be definitely

FIG. 103.—The sunken caldera of Santorin. (After F. Fouqué, Santorin et ses eruptions, 1879; his map here copied from a copy in Neumayr's Erdgeschichte, pub. by the Bibliographisches Institut.) Scale, 1:150,000.

assigned. This difficulty of transitional forms falls to the common lot of nearly all students of natural objects.

Nested calderas.—The conditions leading to the formation of a caldera may recur on a smaller scale at the same volcanic center, so that a second depression of this class is developed within the perimeter of the first. The process may be conceived as repeated several

[1] S. Sekiya and J. Kikuchi, Jour. Coll. Science, Tokio, 1889, p. 106.

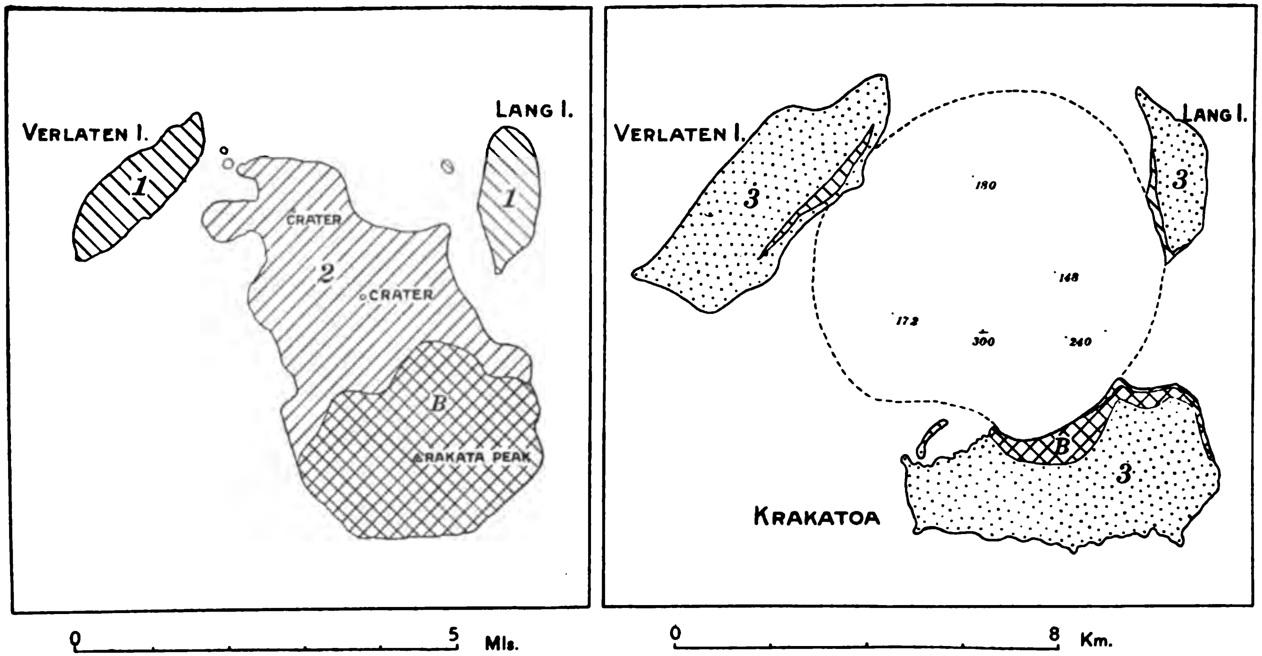


FIG. 104.—Maps showing modifications of the Krakatoa island group by the explosion of 1883. (After R. D. M. Verbeek, Krakatau, 1887, atlas.) That on the left shows the condition before the eruption; that on the right shows the condition after the eruption. *B*, basalt; *1*, older hypersthene andesite; *2*, younger hypersthene andesite; *3*, ash and pumice (hypersthene andesite) erupted in 1883. Depths in meters. According to Verbeek the present central cavity is a sunken caldera.

times. In such cases the form is conveniently described under the name, concentric calderas, or more generally, *nested calderas*. Several examples of such composite forms have been described. (See Fig. 102.)

Sunken calderas.—In a considerable number of cases subsidence is reported to have followed caldera explosion. The resulting depressions may be called *sunken calderas* (Figs. 103 and 104).

Volcanic Sinks.—As already suggested, the "caldera problem" can be partly solved by a general agreement to recognize by actual names the sharp genetic distinction between the "calderas" of Hartung in the Azores and the "calderas" of Dutton in Hawaii. A considerable

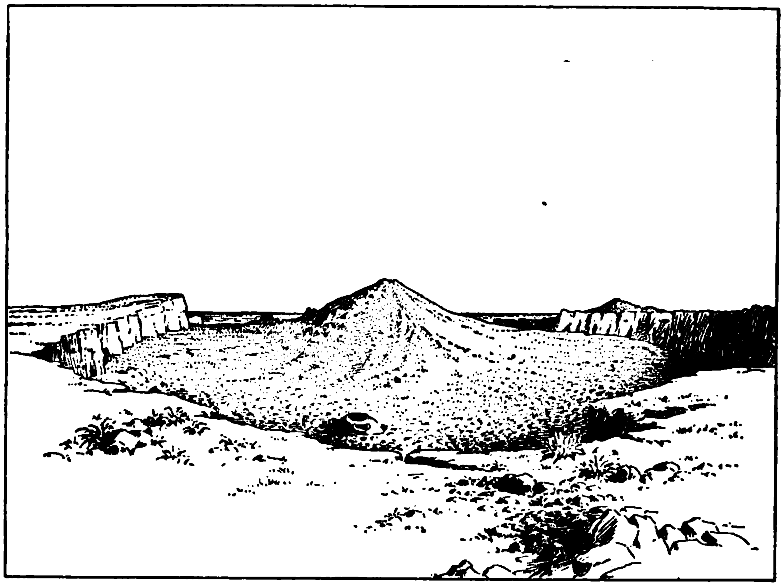


FIG. 105.—View of the Enclos of Réunion, a volcanic sink, in which is the extinct cone, le piton Bory. (After C. Vélain, Mission de l'île Saint Paul, 1880, Pl. 10.) A small adventive crater in the foreground.

number of American authors, including members of the United States Geological Survey and writers of text-books, have adopted Dutton's definition. Of the Hawaiian "calderas" he wrote: "Considered with reference to their origin the evidence is conclusive that they were formed by a dropping of a block of the mountain crust which once covered a reservoir of lava, this reservoir being tapped and drained by eruptions occurring at much lower levels."[1] Diller has followed Dutton in placing the famous depression due to engulfment, at Crater Lake, Oregon, among the calderas.[2]

[1] C. E. Dutton, 4th Ann. Rep., U. S. Geol. Survey, 1884, p. 105.

[2] J. S. Diller, Prof. Paper No. 3, U. S. Geol. Survey, 1902, p. 46.

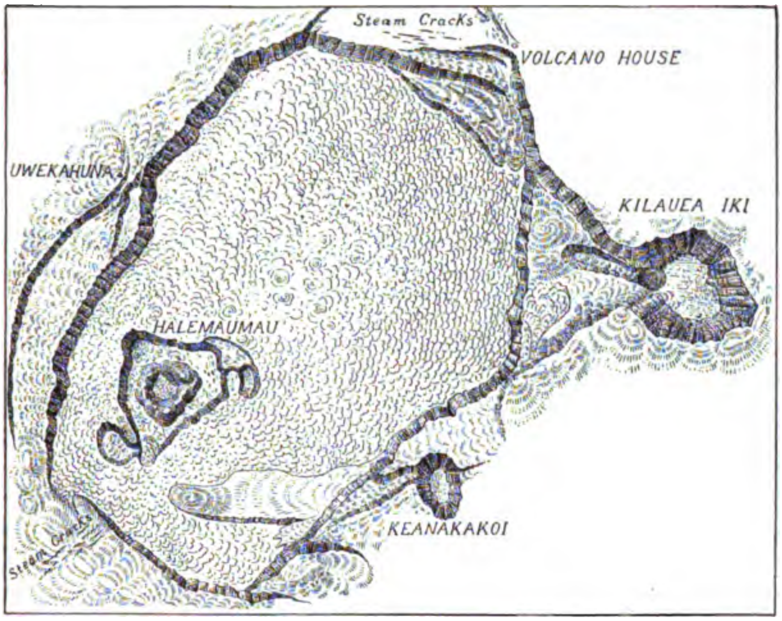


FIG. 106.—Map of the Kilauea sink, Hawaii, in 1886. (After the Government map, by F. S. Dodge.) Scale, 1:57,600.

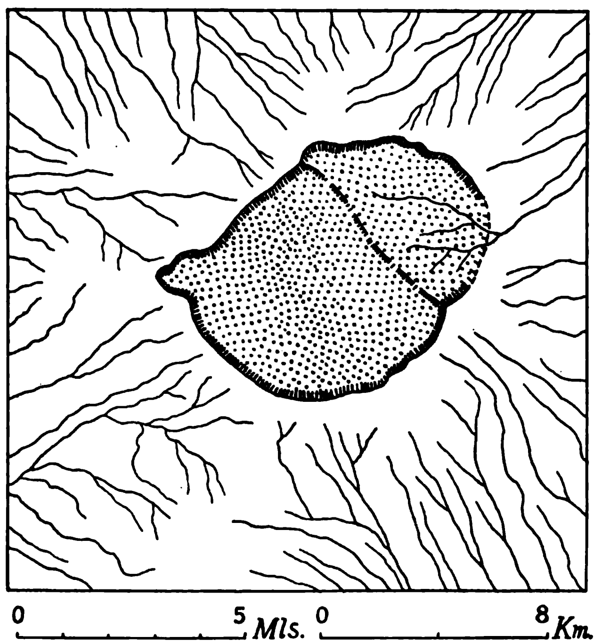


FIG. 107.—Volcanic sink at top of Tengger volcano, Java. (After R. D. M. Verbeek, Description géol. de Java and Madoura, Atlas, sheets C8 and C9.)

It is surely better, in the interests of productive science, to retain the old, established meaning for the word "caldera." The volcanic basins of engulfment, or down-faulting (each with floor area many

FIG. 108.—Section of the sink shown in Fig. 107. (Same ref., Fig. 8 in atlas). *S*, Sunken area underlain by ash, tuff, and lava; *T*, tuff beds of original cone. Faults shown. Heights in meters. Scale, 1:95,000.

times greater than the cross-section of the associated vent) have been called "volcanic sinks" and actual practice, both in writing and teaching, shows that this simple term fills the need and avoids the logical

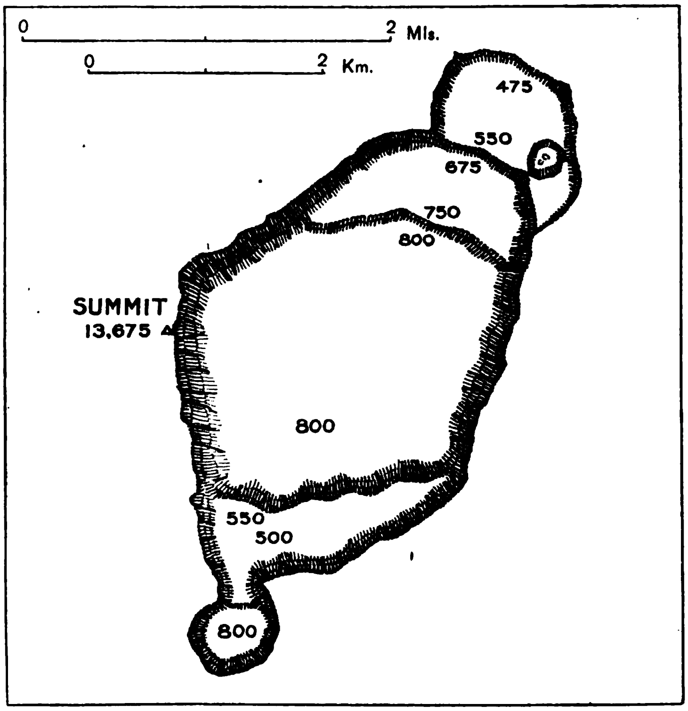


FIG. 109.—Nested sinks at Mokuaweoweo, summit of Mauna Loa, Hawaii. (From Alexander's map of 1885.) Figures show depths below the upper rim, in feet.

difficulty mentioned.[1] Examples of *simple sinks* are illustrated in Figs. 105, 106, 107, and 108.[2]

[1] R. A. Daly, Proc. Amer. Acad. Arts and Sciences, Vol. 47, 1911, p. 110.

[2] Possibly the Tengger depression is better described as a sunken caldera.

Quite recently, du Toit has described a sink so greatly eroded as to have lost its character as a topographic depression. This is the case with the Modder Fontein volcano of the Stormbergen, Cape Province, South Africa. Its tuffs and agglomerates dip inward because of subsidence of a normal volcanic cone during or after the growth of the pyroclastic deposit.[1]

Nested sinks.—More or less concentric sinks have been mapped in Hawaii and elsewhere (Fig. 109). Verbeek has specially emphasized the occurrence of both simple and nested sinks in Java.[2]

Volcanic Rents.—The great gaping depression at the summit of Haleakala in Maui, Hawaiian Islands, is commonly described as a "crater," but Dutton long ago pointed out the fallacy in so doing. He prefers to call this form also a caldera, remarking that it is "strictly homologous" with the main depression (sink) at Kilauea.[3]

During a visit to the summit in 1909 the writer failed to find evidence of this homology. General circumferential faulting, which is topographically so clear at Kilauea, is not evident on the walls of the vast depression on Haleakala. On this problem Dana writes:

> "In my 'Exploring Expedition Report' I suggest that the mountain was fissured across along the lines of the two discharge-ways, and the eastern block shoved off a mile or two. But a subsidence of the masses that occupied them into caverns below, leaving the walls as fault planes, may be more probable. The abyss which received them in this case had been prepared during a long period of undermining through ejections. Still there is some reason to believe in the grander view of a subsidence of the whole eastern block, across the cross-fracturing. The island, as is seen on the map, is abruptly narrowed (instead of widened) at the spots where the Koolau and Kaupo streams reach the sea; and the part to the eastward is small, as if narrowed by such a subsidence. Moreover, the mean height of the eastern crater-wall is lower than that of the opposite or western by five hundred to a thousand feet. A subsidence of a thousand feet increasing in amount to the eastward would account for the narrowing and for the very short eastern radius of the eccentric volcano. The question merits investigation."[4]

The present writer is inclined to believe in Dana's first interpretation of the depression. Brigham long since spoke of it as a "rent," and it seems safer so to designate it rather than as a crater (popular usage) or a caldera. No other example appears to have been recorded.

[1] A. L. du Toit, 16th Ann. Rep. Geol. Comm., Cape of Good Hope, 1912, p. 132.

[2] R. D. M. Verbeek and R. Fennema, Description géologique de Java et Madoura, Amsterdam, 1896.

[3] C. E. Dutton, 4th Ann. Rep., U. S. Geol. Survey, 1884, p. 105.

[4] J. D. Dana, Characteristics of Volcanoes, New York, 1891, pp. 277–278.

PART II

CHAPTER VIII

COSMICAL ASPECTS

Principal Source of Magmatic Heat.—In a brief, necessarily general form, the material of the igneous-rock problem has been laid before the reader. The facts so far presented indicate the chemical and mineralogical diversity of the rock species; their distribution and relative abundance; and the endless variation in the sizes, forms, and relations of igneous bodies. Throughout the preceding chapters the attempt has been made to admit only such descriptions and classifications as are direct expressions of objective facts, though here and there a choice of rival interpretations of certain facts has been compelled before they could be succinctly stated.

In now turning definitely to the explanatory side of the subject, we immediately encounter its most difficult and elusive phase. What is the origin of magmatic heat? The high temperatures actually measurable at volcanic vents or inferred from the character of the intrusive bodies represent a principal part of the igneous-rock problem. Its systematic solution must be founded on a sound cosmogony. In this respect geology must still wait on astronomy for the final word.

Nevertheless, it is well to note that the sure results of astrophysics do not yet negative the geologist's traditional view as to a chief source of the earth's thermal energy. That view was originally founded on the Kant-Herschel-Laplace nebular hypothesis, which involved an earth once molten at the surface, then encrusted through radiation, and still intensely hot within. This conception was not essentially disturbed by Lockyer's meteoritic hypothesis. It must still be subjected to scrutiny after the new planetesimal hypothesis of Chamberlin and Moulton has been more fully tested. At present the latter conception of the origin of the solar system seems to be sounder than the older nebular hypothesis which it is intended to supplant; but a detailed application to the thermal problem of any one of the planets is an extremely hazardous undertaking. More concretely stated, the planetesimal hypothesis does not yet give any certain indication of the former maximum temperature of the earth's outermost shell. It is with that part of the planet that the petrologist is most concerned, and only the relation of the planetesimal hypothesis to the comparatively superficial temperatures need be discussed in this place.

Planetesimal Hypothesis in Relation to the Heat Problem.—Chamberlin's conception of the earth's origin may be summarized in his own words.

"According to the planetesimal theory, the core of the earth is made up of planetesimal matter, perhaps corresponding somewhat in composition to meteorites. After aggregation, the planetesimal matter was probably recrystallized under the influence of the heat and pressure which the aggregation involved, the resulting rock being essentially igneous in its nature. Outside the central core there should therefore be (1) a thick zone made up largely of planetesimal matter, but partly of igneous rocks erupted from below, and partly of sedimentary rocks. The planetesimal matter is assumed to predominate in the lower and major part of this zone; igneous rock, eruptive and irruptive, is assumed to have a somewhat irregular distribution within it; while the sedimentary rock increases in importance above, though remaining throughout a very subordinate constituent. This zone records the growth of the earth from the initiation of volcanic and atmospheric processes to the close of the period of notable growth by accretion. The central core and this thick zone about it represent the Formative eon. (2) The next zone, probably a relatively thin one, is assumed to be made up dominantly of extrusive igneous rocks, with which would be associated subordinate amounts of sedimentary matter and matter gathered in from space. This zone represents the Extrusive eon. (3) Outside it lies the superficial zone in which sedimentary rocks predominate, though associated with not a little rock of igneous origin. The first two zones outside the core are assumed to be universal, while the outermost zone, being composed primarily of material washed down from the land and deposited in the sea, fails to encircle the globe."[1]

Chamberlin further deduces from the hypothesis that the earth's surface was cool enough to support a water ocean even at the stages when the planet was still much smaller than now; and that the surface always thereafter retained temperature of the same order of magnitude.[2]

In other words, the existing statement of the planetesimal hypothesis, as applied to the earth's history, runs counter to the idea that the external shell of the earth, when of approximately its present size, has passed through a period of general fluidity.

1. Chamberlin grants the possibility that the earth in the early "nuclear" stage of its development was hot. The causes of this high temperature are: the quasi-gaseous mode of condensation in the primitive nebular knot; the heat of central compression; and the heat devel-

[1] T. C. Chamberlin and R. D. Salisbury, Geology, New York, Vol. 2, 1906, pp. 134–135.

[2] Op. cit., pp. 108–110.

oped in molecular rearrangement.[1] He assigns the chief portion of internal heat to compression. During this and later stages of planetary growth the speed of heat generation, from all causes, is unknown, but the authors of the planetesimal hypothesis assume a comparatively rapid solidification at the surface of the growing earth. So far, however, no proof of this vital assumption has been presented. If the speed of heat generation reached a certain value, the nucleus would be fluid and incandescent at the surface. In such a condition, radiation would quickly chill the superficial layer and tend to crustify the body. Radiation from a rock surface into free space is about 400 times more rapid at 1100° C. than at 20° C. A temperature near 20° C. would soon characterize the surface of a very thin crust of rock, which is an efficient blanket. As heat is generated by internal compression and by molecular rearrangements, it would tend either to melt the crust intermittently or to keep the crust very thin. The actual alternative would be determined by the ratio of the heat generated to the heat lost in a unit of time. The analogy of existing volcanoes suggests that intermittent fusion of the crust would be the more probable result. No facts have yet been adduced to show that this process would be necessarily restricted to an early stage of the planetary growth. The assumptions of the planetesimal hypothesis do not compel belief in a solid earth even when accretion had first brought the planet approximately to the present size. Only when the (constantly varying) ratio of heat generation to heat loss throughout the epoch of accretion has been determined is it possible to discuss adequately the physical state of the earth's outermost shell at any stage of the planetary development.

2. Chamberlin postulates a transfer of internal heat toward the surface by the extrusion of molten tongues of the more fusible material from the central region, through the otherwise solid material of the earth. These tongues have fluxing power. No indication is given, in the existing statements of the planetesimal hypothesis, as to the speed of this heat transfer. It might be rapid enough to cause nearly or quite perfect fusion of all, or of large areas, of the surface shell of the planet.

3. With certain assumptions Lunn has calculated the earth's internal temperatures expected on the planetesimal hypothesis.[2] The central temperature was found to be practically 20,000° C. Half way to the surface the temperature would be 12,250° C. Since nothing is

[1] T. C. Chamberlin and R. D. Salisbury, Geology, Vol. 2, New York, 1906, p. 100.

[2] A. C. Lunn, in Chamberlin and Salisbury's Geology, Vol. 1, 2d ed., New York, 1906, p. 564.

known about the behavior of matter at such temperatures and at the pressures reigning in the deeper region of the earth, it is impossible to assert that the growing body would be chiefly in the solid state. Arrhenius holds that at such temperatures as those quoted from Lunn all known substances would be in the critical state. If so, there is a clear probability that the heterogeneous materials of the growing planet would have become stratified; the slow rise of the lighter substances and the slow sinking of the heavier must take place unless they were infinitely viscous. Such convective overturn, bringing upward the very hot material at the center, might be rapid enough to cause complete fusion of the superficial shell. Here again the existing statement of the planetesimal hypothesis is not complete enough for the needs of igneous geology.

4. Nor does that statement take proper account of the low densities of the outer planets. The average densities of the earth, Jupiter, Saturn, Uranus, and Neptune are respectively about 5.5, 1.3, 0.7 1.2, and 1.1, if water be assumed to have unit density. The masses of Jupiter, Saturn, Uranus, and Neptune are respectively about 316, 95, 15, and 17 times the mass of the earth. At the surface of each of these planets the force of gravitation is, respectively, about 2.65,1.18, 0.91, and 0.88, if gravity at the earth's surface be taken as unity. Authorities in cosmical physics generally attribute the low densities of the four greater planets to very high temperatures, and Jupiter is often spoken of as a "semi-sun." The only alternative to assuming high temperature for each of the four greater planets is to assume that it is entirely composed of one or more very light elements; this view is taken by Chamberlin.[1] Such a highly specialized constitution is a deduction from the planetesimal hypothesis in its existing form of statement, which implies that the thermal evolution of the earth was not essentially different from that of the greater planets. Since, on the other hand, high authorities in astronomy prefer to credit very high temperatures for the surfaces of Jupiter and Saturn, a heavy burden of proof rests on anyone who claims a continuously solid surface shell for the earth during the latter half of the period of its growth by planetesimal accretion. The sun is known to be largely composed of heavy elements (iron, calcium, barium, titanium, platinum, and other metals); gravity at the sun's surface is nearly 28 times that at the earth's surface, and the internal pressures of the sun are incomparably greater than those of the earth. Nevertheless, the mean density of the sun (1.39) is only slightly above that of water. The sun's low density is obviously explained by his high temperature

[1] T. C. Chamberlin and R. D. Salisbury, Geology, Vol. 2, New York, 1906, p. 58.

rather than by his chemical constitution. This fact must be considered in the problem of the outer planets.

Again, the planetesimal hypothesis as stated and applied to earth history, does not clearly reconcile the fact that the sun has a surface temperature of approximately 6000° C., with the assumption that the earth remained cool enough to support a water ocean during the latter half of its period of accretion. It is, of course, true that the condensation of the enormously greater mass represented in the sun must produce much higher temperature than that due to the condensation of the earth mass; but, on the other hand, the total loss of heat through geological time has been many millions of millions of times greater. As the mechanism of heat production is assumed to be the same for earth and sun, one may well question the deduction that the earth, in its later history of accretion, did not pass through a stage of incandescence at the surface. Even the moon, with its relatively feeble capacity of heat production by self-compression, seems to have been in a magmatic state close to its surface, if not actually at its surface.

5. Finally, the ocean ought to be more salty than it actually is if Chamberlin's view is correct, that the water ocean has existed from the time when the growing earth had about half its present volume.[1] Computations of the age of the ocean from salinity data are sufficiently reliable to cause serious embarrassment to the geological student, who may feel compelled to adjust all the myriad recorded events of post-Keewatin time to fit the 80,000,000 years deduced by the calculation. If, in addition to the salt supply poured into the ocean during Keewatin and later time, the ocean were to have received the highly soluble chlorides during the indefinitely long epoch implied in doubling the earth's volume by accretion, it is certain that the existing ocean must be a much stronger brine than it is at present.

We may conclude that the planetesimal-nebular hypothesis, like the older gas-nebular and meteoritic hypotheses, does not forbid belief in: (a) a former molten stage for the earth's external shell; (b) the density stratification of this planet; (c) a fairly uniform composition for the surface shell; (d) general magmatic temperatures not more than a few miles below the surface, throughout geological time. Important as the planetesimal hypothesis is in cosmogony, it does not seem to affect the traditional view of geologists as to the thermal condition of the globe. The first and fourth of the postulates above listed have formed the basis of most modern theories of vulcanism and of igneous action in general. The second and third postulates are less universally made but they are almost certainly corollaries of the first-

[1] T. C. Chamberlin and R. D. Salisbury, Geology, Vol. 2, New York, 1906, p. 109.

mentioned postulate as to a former molten condition of the earth's external shell.

The discussion of these assumptions will be continued here only with reference to a few relevant studies of recent date.

Density Stratification of the Earth.—Daubrée and other geologists have expressed the view that the meteorites represent, in a general way, the average stuff constituting the earth body. Though the total weight of the known meteorites is only a few tons, their great number and their wide distribution over the earth have suggested that they represent qualitatively a sample of the cosmic material composing at least the inner part of the solar system. Farrington's new average for the more trustworthy chemical analyses, including 318 analyses of "iron" meteorites and 125 analyses of stony meteorites, has prompted him to re-state this hypothesis with approval.[1] He writes:

> "The large proportion of iron in the constitution of the earth indicated by meteorites is in accord with the earth's density, rigidity, and magnetic proportions. Assuming the density of the rocks of the earth's crust to be 2.8, which may be too high, and combining with it metal of the density of 7.8, which is an average of the density of iron meteorites, it will be found that 77.58 per cent. of metal will be required to obtain a density of 5.57, that of the earth as a whole. This is very nearly that of the sum of the metals in the above result after eliminating the proportions present as oxides. Such a proportion of iron would seem to be in accord, as has been stated, with the earth's rigidity and magnetic properties."

The percentage of metal so calculated for the earth corresponds to a globe with a radius less than 325 miles (520 km.) shorter than the average radius of the earth.

This estimate is subject to various corrections. A leading one will allow for the fact that the metallic meteorites attract attention more readily than the stony meteorites. In fact, only of late years have the tektites been recognized as of extra-terrestrial origin. For this reason the metallic meteorites are doubtless considerably over-emphasized in the world collections. If a complete collection of meteorites were made and analyzed, its average composition would almost certainly be more salic than the average shown in Farrington's table. It may be that the non-metallic portion would have a ratio of the same order as that of the outermost 1500-kilometer shell of the earth to the mass of the whole planet. For quite independent reasons founded on seismic study, Wiechert, Oldham, and others have deduced

[1] O. C. Farrington, Publication No. 151, Field Museum of Natural History, Chicago, 1911, p. 214.

1500 kilometers as the approximate thickness of the earth's silicate shell, the great central mass being metallic.[1]

The facts of terrestrial density, the facts of seismology, and the facts derived from meteoritic studies thus agree in suggesting a coarse stratification for the earth as a whole, with the silicate matter chiefly or wholly confined to a comparatively thin external shell. This view has been adopted by Suess in the last volume of his great work.[2]

According to the older nebular and meteoritic hypotheses, this general stratification is an expected feature of the terrestrial globe. The explanation is comparatively simple if it be granted that the whole planet was once fluid, even though highly viscous at the core. Immiscibility of metal and silicate, together with the influence of differential density, must ultimately cause the metallic core to separate from the silicate shell. This process, so commonly credited as the essential one, has an obvious parallel in the gravitative sorting of the material in an assaying crucible.

The planetesimal hypothesis, as stated by Chamberlin, recognizes the formation of the outer silicated shell by repeated extrusion of molten "tongues" of the appropriate composition. As already noted, this suggested mechanism is not only complicated; it fails to allow for the high probability that all the important substances of the earth's interior, if subjected to the temperatures actually calculated on the planetesimal hypothesis, must be in the critical state. Moreover, the hypothesis fails to account for the failure of metallic alloys with low fusion points among the known extrusive "tongues."

Yet it is important to note that even the authors of the new planetesimal hypothesis are also inclined to share the orthodox view that the earth is coarsely stratified.

Whether the external silicated shell was all simultaneously molten or has been formed piecemeal by successive eruptions of large igneous "tongues" from the deep interior, gravity must directly affect the liquid magmas involved. The important question arises concerning the degree and kind of density stratification to be expected in the sili-

[1] E. Wiechert, Nachrichten der Gesellschaft für Wissenschaften, Göttingen, 1897, p. 221; and Deutsche Rundschau, 1907, p. 376. R. D. Oldham, Quart. Jour. Geol. Soc., 1907, p. 347. The idea that the high pressures of the earth's interior might suffice to give even silicate material the demonstrated high density there existing is one often expressed but it savors of the mystical. Modern high-pressure experiments have already suggested the improbability of this hypothesis even if the earth had room temperature at its center. Allowing for the actually high internal temperatures, it seems clear that the reigning pressure at the globe's center could not give the required density to ordinary rock matter.

[2] E. Suess, Das Antlitz der Erde, Bd. 3, zweite Hälfte, Vienna and Leipzig, 1909, p. 625.

cated shell itself. In Chapter XII, page 230, will be found a collation of the many observations tending to show how generally even small igneous bodies are stratified according to density. For the present these evidences of a general structure in the earth's interior will be held in reserve while other facts of similar import will be discussed.

Earth's Sedimentary Shell.—The visible sedimentary shell of the earth is relatively thin, averaging probably less than 1/2 mile in thickness. It is a ragged, discontinuous "pellicle" on the earth.[1] In some narrow geosynclinal belts it shows local thicknesses of 40,000 feet or more. The visible material of the sedments has been largely, if not principally, derived from the pre-Cambrian granites and orthogneisses. The existence of this sedimentary shell of the earth has a very important relation to the origin of the less abundant igneous-rock species. (See Chapters XVI to XX.)

Earth's Acid (Granitic) Shell.—Beneath the sedimentary rocks on every continent, the igneous complex of early pre-Cambrian age has been found and geologists are now disposed to regard this terrane as composing the larger part of each continental plateau, probably underlying at least one-third of the whole earth's surface. It is not known to exist in the middle part of the Pacific basin, and perhaps the terrane is actually absent in that region as well as in parts of the Indian and South Atlantic basins.

The basement complex is typically represented in the Canadian and Fennoscandian shields. Already enough field work has been done to warrant a statement of the average composition of the terrane in these great outcrops; it is that of common granite.

The depth of the pre-Cambrian complex is, of course, unknown. From its uniformity in constitution at the various levels laid bare by Cambrian and later denudation it seems likely that the average depth is to be measured in miles rather than merely in thousands of feet.

We may conclude that the sediments of the continents at least rest on a general terrane averaging a granite in composition. Though this complex may not extend under the whole of the great ocean-basins, it is fair to call it an earth shell.

Since most of the acid shell seems to be of intrusive character, we must now inquire as to whether the existing chemical composition of the pre-Cambrian batholiths is primary. Can this granitic material be explained as the result of the wholesale fusion of sediments derived from an antecedent general igneous type of different composition? Such an explanation for the world granites has been offered by a number of the older geologists. It is now not seriously entertained

[1] See F. W. Clarke, The Data of Geochemistry, 2d edition, Bull. 491, U. S. Geol. Survey, 1911, p. 30.

for most of the post-Cambrian batholiths, but the evidence against this explanation for the much more voluminous pre-Cambrian bodies is not so directly manifest. Yet reflection will go far to convince the reader that it fails also in this case.

The only probable rock-type which through weathering and erosion could be conceived to form the required amount of sediments is either basalt or andesite. Of these two, basalt has, much more clearly than andesite, the known volume and geological relations of a general, primary earth magma. Yet the derivation of the required sediments by leaching and washing would be less difficult to conceive in the case of andesite; and, in the interests of safe reasoning, we will assume that the primary matter from which the imagined pre-Cambrian sediments were derived was andesite. It will be further assumed that this andesitic land mass would have an average composition like that of the average andesite now exposed on the earth. This composition is closely indicated in the calculated average of eighty-seven chemical analyses. (See Col. 46 of Table II.) In Col. 1 of Table II the estimated average analysis of the pre-Cambrian granites (and orthogneisses) is stated. The soda percentages are seen to be nearly identical in the two averages, while potash is about twice as abundant in the granite as in the andesite. For the present argument it will suffice to examine the imagined process by which the potash is increased so as to reach the proportion in the granite.

The percentage of sodium in the average andesite is 2.66; the potassium percentage is 1.69. The corresponding percentages for the granite are 2.40 and 3.74. Clarke's average for the river-waters of the present day shows the ratio of sodium to potassium to be 5.79 to 2.12. It is safe to assume the ratio for the average pre-Cambrian rivers to be not less than 4 to 1. If, then, the imagined andesitic land lost to the ocean 4 parts of its sodium, it would lose at least 1 part of its potassium.

Let us further assume that the total area of the pre-Cambrian granitic terrane to be derived originally covered only 50,000,000 square miles and that it was only 2 miles in depth—certainly low estimates in each instance. To produce this volume (100,000,000 cubic miles) of sediments, later to be metamorphosed into granite, the weathering of at least 250,000,000 cubic miles of the primary andesite would be required. During that prodigious denudation all the sodium of at least 150,000,000 cubic miles of the andesite must have gone into the ocean. There it would remain in solution if the ruling conditions were then the same as in the present ocean. Calculation shows that the sodium contained in such an amount of average andesite is about three times the entire mass of the sodium in the existing ocean. Since there is no known method by which its water could be so much sweetened during the intervening ages, it seems wise to conclude that the initial assumption is fundamentally wrong. The reasoning is similar, though yet more conclusive, in the case of the postulated basaltic continent.

Without further amplification, the argument against a derivation of the material of the earth's acid shell by the secular weathering of andesitic or basaltic continents, may be regarded as sufficiently strong. No other igneous type is found in quantity large enough that it could be regarded as representing the original lands.

Clarke has calculated that "the complete decomposition of a shell of igneous rock 1/3 mile thick would yield all the sodium in the ocean."[1]

The most reasonable view seems, therefore, to be that the earth's acid shell is essentially composed of primary igneous material, which, for the most part, has been re-fused and intruded in the forms of the pre-Cambrian batholiths.[2]

Earth's Basaltic Shell (Stratum, beneath the "Crust").—The acid shell is obviously underlain by at least local bodies of magma which from time to time has traversed that shell and has crystallized as basalt or the chemically equivalent diabase, gabbro, etc. Both chemical and field relations show that this basic magma cannot possibly be due to the fusion of ordinary sediments. Not so directly, but in the end just as convincingly, those relations show that the greater basaltic masses (fissure eruptives) have not originated by the differentiation of intermediate magma just before their eruption. The acid pole of such a hypothetical splitting ought to be on a similarly large scale and, being of lower specific gravity than the basic pole, it ought, according to the plain common sense of the case, to be erupted before the basalt. In numberless cases, and particularly in the basaltic-plateau regions, such association of acid magma entirely fails. Basalt, diabase, and gabbro must be regarded as primary earth-magma.

As indicated in Chapter III, basaltic magma is the only one represented in all the larger divisions of the earth's surface. The visible granite is much more voluminous than all the visible bodies belonging to the gabbro clan taken together, but the extrusive members of this clan are more evenly spaced on the globe. The granites are generally, if not always, confined to orogenic belts; the basaltic rocks appear indifferently in mountains, plains and plateaus, both subaerial and submarine.

[1] F. W. Clarke, Data of Geochemistry, Bull. 491, U. S. Geol. Survey, 2d edition, 1911, p. 29.

[2] After writing this section the writer has found that Michel Lévy in the Bull. soc. géol. France, Vol. 16, 1887, p. 110, had already expressed essentially the same conclusion.

When magma has been extruded on the largest scale and most rapidly, through narrow fissures in which it evidently remained too brief a time for the incorporation of foreign material (fissure eruption), that magma has always been basaltic. We have also seen that among all the igneous types the basalts have had the greatest persistence in geological time, from the earliest recorded pre-Cambrian to this moment. (See Appendix B and page 56.) The gabbro clan is that one most steadily represented in the standard eruptive sequences so far described, though probably all such sequences for the continental plateaus, if fully recorded, would include pre-Cambrian granite.

Finally, the basalts and most of the other members of the gabbro clan, of whatever region or geological date, have always had striking uniformity of chemical composition.

These facts suggest a primary origin for all or most of the world's basaltic or gabbroid magma. (See Chapter XV.) They must have partly furnished the motives which prompted von Cotta, long ago, to record his belief in a continuous basaltic shell underlying the earth's acid shell. Before him Bunsen had developed his well-known hypothesis of two fundamental magmas, the "trachytic" and the "pyroxenic."[1] Von Cotta, going a step farther, conceived that the more basic magma underlies the other and, further, that the former has long been the only fluid magma. His own words will best state his position:

"Bunsen hat, wie gesagt, allerdings sehr zweckmässig einen allgemeinen Unterschied zwischen trachytischen und pyroxenischen Gesteinen auch chemisch festgestellt, nachdem ich längst geologisch sie zu unterscheiden pflegte, in Wirklichkeit gehen aber auch diese beiden Gruppen durch Mischlinge ineinander über. Bunsen nimmt zur Erklärung der Thatsache an, es beständen zwei verschiedene vulkanische Herde im Erdinnern, ein trachytischer (saurer) und pyroxenischer (basischer), das ist eine Hypothese, ein sehr interessante, vielleicht eine sehr fruchtbare Hypothese, aber es ist doch nur eine Hypothese. Ist es denn nicht ebenso gut möglich, dass der jetzige Herd der vulkanischen Thätigkeit nur pyroxenisch ist? Dass aber alle Eruptionen eine kieselreiche Kruste durchdringen müssen, in welcher sie durch allerlei Zufälle bis zu einem gewissen Extrem (dem normaltrachytischen) ungleiche Mengen von Kieselerde aufnehmen? Und darüber hinaus noch als quarzhaltige Gesteine! Mir scheint das sogar leichter denkbar, als das Neben- oder Untereinander-Bestehen von zwei ihrer chemischen Natur nach verschiedenen vulkanischen Herden, zumal da ein solches Nebeneinander-Bestehen in allen geologischen Zeiträumen stattgefunden haben musste. . . . . .

"Wir haben es hier nur mit der heissflussigen Region und mit der festen Kruste über ihr zu thun. Nehmen wir an, diese letztere sei aus vorzugsweise kieselreichen Substanzen gebildet worden, während die flüssige Region in

[1] R. Bunsen, Pogg. Annalen der Physik u. Chemie, Vol. 83, 1851, No. 6, p. 197.

ihrer allgemeinen Zusammensetzung ungefähr der normal pyroxenischen Mengung entspricht, so scheint mir diese Annahme auszureichen, um alle vorhandene Mannigfaltigkeit der Gesteine im Allgemeinen zu erklären. Die aus dem Innern emporgepressten heissflüssigen, sehr basischen Stoffgemenge lösten auf ihrem Wege, je nach den Umständen, viel, wenig, oder gar nichts von der vorhandenen kieselreicheren, festen Kruste (sowohl der erstarrten als der abgelagerten) auf und näherten sich dadurch mehr oder weniger den extremen trachytischen Endgliedern. Hierdurch erklärt sich die stoffliche Verschiedenheit der Eruptivgesteine, während ihre mineralogische Verschiedenheit (die Ausbildung der einzelnen Mineralien) und die Ungleichheit ihrer Textur stets eine Folge der besonderen Umstände der Erstarrung war, je nachdem diese schnell oder langsam unter geringem oder hohem Druck, unter Zutritt von Wasser oder nicht, erfolgte." [1]

The general conception of a basaltic substratum was reached, apparently quite independently, by W. L. Green and briefly outlined on page 61 of Part II of his "Vestiges of the Molten Globe," published at Honolulu in 1887. In 1901 the present writer was independently led to it as the only workable hypothesis for the explanation of the common eruptive sequence illustrated in principle at Mount Ascutney, Vermont.[2]

Irrespective of hypothesis, the known distribution of basaltic eruptions, both in time and space, demands either a very extensive series of subterranean chambers filled with basaltic material or else a continuous basaltic substratum. Even if the basaltic eruptives originate in separate compartments, these must have large size, as shown by the vast areas of country rocks which have been more or less simultaneously penetrated by basaltic injections. So great must be the total area underlain by these imagined compartments of the earth's interior, that the whole must form an earth-shell fairly so called.

Earth's "Peridotitic" Shell.—We have thus arrived at a mental picture of the outer silicated layer of the earth which is derived directly from proved facts. That layer is formed exteriorly of a discontinuous sedimentary shell, a possibly discontinuous underlying "granitic" or "acid" shell, and below that again a basaltic shell, either continuous or discontinuous.

There are no positive facts compelling a definite answer to the question as to what type of silicate matter underlies the basaltic shell. Here we must return to speculation which can now be only suggestively affected by actual observations. If the known meteorites together really represent anything like a sample of earth substance, some light on this problem is offered in the averages recently compiled for the chemical analyses of stony meteorites. In Table VII, Col. I

[1] B. Cotta, Geologische Fragen, Freiberg, 1858, pp. 76–78.

[2] R. A. Daly, Bull. 209, U. S. Geol. Survey, 1903, p. 110.

gives Farrington's average for 443 analyses, including those of 318 iron meteorites; Col. 2, his average for 125 analyses of stony meteorites. Column 3 shows Merrill's average for 99 analyses of stony meteorites.[1]

TABLE VII.—AVERAGE COMPOSITION OF METEORITES

	1	2	3
Fe	68.43	11.46	11.61
SiO_2	11.07	39.12	38.98
MgO	6.33	22.42	23.03
FeO	4.55	16.13	16.54
Al_2O_3	.74	2.62	2.75
CaO	.65	2.31	1.77
S	.49	1.98	1.85
Ni	6.44	1.15	1.32 (Ni, Co)
Co	.44	.05	
Na_2O	.23	.81	.95
P	.14	.04	.11
Cr_2O_3	.12	.41	.84 (Cr_2O_3, Fe_2O_3)
Fe_2O_3	.11	.38	
NiO	.06	.21	....
K_2O	.05	.20	.33
MnO	.04	.18	.56
C	.04	.06	....
Cu	.01	....	....
Cr	.01	....	....
P_2O_5	.01	.03	....
TiO_2	.01	.02	....
SnO_2	.01	.02	....
H_2O	....	.20	....
Ni, Mn, Cu, Sn,	....	.02	....
	99.98	99.82	100.64

Assuming that the stony meteorites correspond to a rough average for the material in the earth's silicated shell, it follows that a large proportion of it must be non-feldspathic and peridotitic in composition.

Many authors have reached the same speculative result in attempting to draw a parallel between meteoritic and terrestrial material. However, no one has ever progressed much beyond the hypothetical stage in the inquiry. The most that can be said is that there is no known fatal objection to regarding the earth's silicated shell itself as stratified according to density, while that shell as a whole has the approximate average chemical composition of the stony meteorites.

Relation of Planetary Shells to Petrogenesis.—The foregoing part of this chapter has been occupied partly with facts, partly with speculation concerning the necessarily invisible interior of the earth. Relatively meagre as the facts are, they unquestionably point to the

[1] O. C. Farrington, Publication 151, Field Museum of Natural History, Chicago, June, 1911, pp. 211–213; G. P. Merrill, Amer. Jour. Science, Vol. 27, 1909, p. 471.

existence of the successive sedimentary, "granitic" or "acid," and basaltic shells, using the last word with the elastic meaning above indicated. The reasons are ample for the belief that only those three earth-shells are actually concerned with the formation of the visible igneous rocks. Each of the two overlying shells is, in part, visible at the earth's surface. The basaltic shell, as such, is nowhere visible; its existence is inferred. Before a fruitful attack on the general petrogenic problem is possible, some kind of a definite idea as to the nature of the deepest of the three shells must be obtained.

The conception that the basaltic shell is a continuous substratum enveloping the whole earth is not refuted by any of the facts of petrology, but it remains, and probably must remain, an undemonstrated assumption. Many petrologists have expressed or implied their refusal to venture so far into speculation. Yet it is already clear that without some such fundamental assumption the problem of the igneous rocks must forever remain insoluble. If, on the other hand, the basal hypothesis contains within it the explanation of every one of the countless millions of facts which may be recorded of the visible rocks, and if no other basal assumption can do this, the tradition of true science compels adhesion to the hypothesis thus successful in correlation. The earth's interior is no more removed from sensible contact than the interior of a molecule or than the hypothetical ether. As physics and chemistry have been vitalized and made practically useful through their undemonstrable hypotheses, so petrology must become a more enriching, helpful science through its fundamental hypotheses. It is the principal aim of this work to sketch the grounds for the belief that the assumption of a universal basaltic substratum may be hopefully regarded as the first step in a correct explanation of igneous-rock species, of igneous bodies, and of igneous action on the earth. The full value of the conception of a basaltic substratum is only to be known by its fruits.

"Average Igneous Rock."—Before proceeding to the specific application of this hypothesis, we may pause for a brief extension of the speculative inquiry. Of late years the question as to the chemical nature of the "average igneous rocks" has been proposed by several writers. Most of them (Harker, Clarke, Washington) have assumed that the chemically analyzed rock specimens, taken together, more or less closely represent this average. In his latest computation Clarke states that the arithmetic mean of all the good analyses should give a fair chemical average for the outermost ten-mile shell of the earth.[1] Mennell and others, including the present writer, have pointed out the overwhelming predominance of the granites in that shell down to a

[1] F. W. Clarke, Bulletin 491, U. S. Geol. Survey, 1911, p. 22.

probable depth of several miles.[1] Our hypothesis of a stratified earth, as stated, implies that the visible igneous terranes consist partly of that granitic material, partly of more basic material erupted from the substratum, and partly of the more or less modified material of those shells. Though the basaltic matter and its derivatives are exposed in relatively small total volume, they occur in the form of distinct bodies which are probably much more numerous than the granitic bodies. The small average volume is largely counterbalanced by the greater number and wider distribution of the more basic masses. For this and other reasons the petrographers and chemically-minded geologists have devoted special attention to the less voluminous rock types. In Osann's compilation of 2431 of the world's analyses (1884–1900) the number stated for members of the granitic clan (550) is nearly equal to the number stated for members of the gabbro clan (490). These together make nearly half the total number of analyses. Of the other half about 400 analyses belong to the diorite clan. As shown in Table VIII, the mean of average granite and average basalt is almost identical with the average diorite or andesite.[2] It is, then, not surprising that the average of the world analyses (Col. 6) is close to the average for diorite or andesite.

TABLE VIII

	1	2	3	4	5	6
	Average granite	Average basalt	Mean of 1 and 2	Average diorite	Average andesite	Average rock (Washington)
No. of analyses	236	161	....	89	87	1,811
	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.
SiO_2	70.47	49.65	60.06	59.19	60.35	58.96
TiO_2	.39	1.41	.90	.81	.78	1.05
Al_2O_3	14.90	16.13	15.52	16.51	17.54	15.99
Fe_2O_3	1.63	5.47	3.55	3.02	3.37	3.37
FeO	1.68	6.45	4.06	4.17	3.17	3.92
MnO	.13	.30	.21	.13	.18	....
MgO	.98	6.14	3.56	3.93	2.78	3.88
CaO	2.17[3]	9.07	5.62	6.47	5.87	5.29
Na_2O	3.31	3.24	3.28	3.39	3.63	3.96
K_2O	4.10	1.66	2.88	2.12	2.07	3.20
P_2O_5	.24	.48	.36	.26	.26	.38
	100.00	100.00	100.00	100.00	100.00	100.00

[1] F. P. Mennell, Geol. Mag., Vol. 1, 1904, p. 263, and Vol. 6, 1909, p. 212.

[2] Some quartz diorites are included in the average of Col. 4 in order to counterbalance the influence of certain gabbroid types called "diorites" and used in making this average. Loewinson-Lessing states (Geol. Mag., Vol. 8, 1911, p. 249) that the mean of average gabbro or basalt and average granite is a syenite. On comparing Table VIII with Columns 16, 17, and 24 of Table II, it will be seen that this mean distinctly differs from average syenite, as specially observable in the magnesia, lime, soda, and potash percentages.

[3] Includes .06 per cent. BaO and .02 per cent. SrO.

While the average of the exposed igneous rocks is not a diorite but a granite, the mean composition of the earth shells engaged in igneous action may be close to a diorite. In that sense and in that sense only can the figures of Clarke, Washington, or Harker be regarded as nearly representing the "average igneous rock."

Speculation as to the Primitive Differentiation of the Earth's Silicate Mantle.—This does not necessarily mean that the earth's silicated shell was, in its upper part, originally of dioritic composition. Yet if that shell were once greatly superheated, the granitic and basaltic materials may then have been in fairly uniform solution; and they may have later separated, by a kind of liquation, as the temperature slowly fell. Such in principle is Durocher's explanation of the primitive earth magmas which were to compose the visible rocks.[1]

As we shall see later, there are direct reasons for believing in an "antagonism" or limited miscibility between granitic magma and basaltic magma, whereby these tend to separate according to their densities. The facts of geology directly suggest the probability of such gravitative stratification of the earth's primitive shell. It is much more speculative and uncertain to hold that the surface shell of the earth, when liquid, was originally constituted like molten andesite or diorite. Fortunately for nearly all the practical applications of petrogenic theory, this point needs no decision.

A minimum degree of recency for the separation of the granitic and basaltic shells is suggested by the composition and structure of the pre-Cambrian terranes. The earth's "crust" must have been solidified before the clearly extrusive basalts (greenstones) of the Keewatin group in Canada were poured out. Similarly, the extrusive "metabasites" of the Finnish Bottnian and Kalevian are among the very oldest known rocks. The "crust" upon which these ancient masses were extruded was doubtless either granitic or dioritic. No other composition can be assumed for this "crust" without involving insuperable difficulties in explaining the dominant, batholithic formations of the pre-Cambrian complex. If the "crust" were dioritic, its débris should somewhere be abundant in the earlier pre-Cambrian sediments. Yet those sediments show plain evidence of having been derived chiefly from granitic lands of great extent. Again, on this assumption, the actual pre-Cambrian granites could only be explained as the products of separation or differentiation in huge masses of the dioritic crust which had been remelted. It would then be necessary to assume the possibility of such differentiation in the later batholithic period, while denying its control in the earlier period when the "crust" diorite as a whole was molten. This and other difficulties are avoided

[1] J. Durocher, Annales des Mines, Vol. 11, 1857, pp. 217–259.

if we assume a granitic "crust" for the earth which antedated the eruption of the oldest greenstones of the pre-Cambrian terranes.

It is not necessary to believe, nor is it likely, that the earth's granitic shell is sharply marked off from the basaltic shell. From the analogy of differentiated sills and similar bodies, we may more reasonably imagine a transitional phase between the two shells. How important that phase is volumetrically, and how diversified it is chemically, are of course questions not to be definitely answered. The significant fact is that the earliest pre-Cambrian greenstones are essentially of the same chemical nature as the average modern basalts. The uniformity of composition exhibited in the great lava-floods of the pre-Cambrian as well as in those of later dates implies that the eruptible material of the substratum has been basaltic throughout the period during which the visible igneous bodies have been erupted. This again implies that both the granitic shell and the transitional phase beneath it were solidified in the pre-Keewatin time. If the outer part of the earth has been cooling ever since, some of the basaltic substratum has since been frozen to the overlying shells.

The "crust" of the earth may thus be conceived as composed of parts which, in downward succession, may be listed as follows:

1. The discontinuous sedimentary shell.
2. The continuous (?) granitic shell.
3. The continuous (?) transitional shell.
4. The continuous solid shell of basaltic composition.

Beneath that "crust" is the basaltic substratum which is still hot enough to flow and, in liquid form, to penetrate the crust if the pressure is considerably relieved.

Physical Condition of the Substratum.—It is not necessary to assume that the basaltic shell of the earth is molten as a whole, or that, as a whole, it has been molten since the Keewatin division of pre-Cambrian time. Where so little is known about it or can be directly observed, the state of the substratum is subject to almost as many hypotheses as have been applied to the physical nature of the earth's interior magma in general. The primary reservoirs of magma have been conceived by different speculative writers to be:

(1) Multiple bodies of isolated liquid rock, still molten because of the earth's primitive heat;

(2) A single substratum of rock, kept liquid by primitive heat; or

(3) Multiple bodies made temporarily molten in an otherwise solid earth.

There are no known facts compelling belief in any of these hypotheses for the basaltic substratum. The third view, that it is, in general, truly solid or crystalline, involves the special difficulty of requiring the local introduction of an enormous amount of thermal energy. The latent heat of fusion for crystallized basalt or gabbro is from one-fourth to one-fifth of its total melting heat measured from 0° C. To find the source of such additional heat in radioactivity is to pile difficulty on difficulty, for the local development of such a furnace is hard to conceive in an earth shell which had already become cooled enough for complete crystallization. If uranium or other suitable radioactive matter of the postulated abundance were originally in the shell, that shell could not have become crystallized without a temporary lull in the atomic transformation; an improbable condition. On the other hand, a mechanism whereby new radioactive matter is brought into the shell is hard to imagine.

The first hypothesis had the advantage of making relatively easy the reconciliation of the proofs of a very rigid earth with the facts of igneous geology. But it is quite possible that this reconciliation is possible for a very different reason. Several investigators, especially Bridgman and Adams, have recently shown that a confined liquid, like a soft solid, under very high pressure may become extremely rigid. Glass at 24,000 atmospheres becomes much stronger than steel is at atmospheric pressure. Under great pressure paraffine (like rubber) will indent steel and the ordinarily soft mineral, fluorite, becomes less plastic than steel.[1] These experiments suggest that the entire basaltic substratum is possibly a true fluid, which resists tidal deformation so well because of internal friction developed by great pressure.

The objection might possibly be urged that a solid crust would not be in stable equilibrium if resting on a general fluid substratum. Since silicate matter is more dense in the solid state than in the liquid state and since heightened temperature means lowered density, one might assume that there would be danger of crustal foundering. Such, indeed, was the basis of Kelvin's well-known speculation on the origin of the earth's internal temperature at the time of crustification. But the objection loses much of its force when it is assumed, as here, that the globe is stratified, with its shells becoming more ferromagnesian with increase of depth. Other vital considerations on this topic are discussed by the writer in earlier publications.[2]

Since the hypothesis of a continuous, eruptible substratum is also the simplest of the three so far conceived it may be favored in one's attempt to secure a mental picture of the substratum in action. However, the lack of full knowledge on this matter does not destroy the

[1] P. W. Bridgman, in Proc. Amer. Acad. Arts and Sciences, Vol. 47, 1911, p. 53. F. D. Adams, Jour. Geology, Vol. 18, 1910, p. 500; ibid., Vol. 20, 1912, p. 97.

[2] Amer. Jour. Science, Vol. 22, 1906, p. 201; ibid., Vol. 26, 1908, p. 32.

probability that liquid parts of the basaltic substratum *have* participated in all igneous action. That probability is derived from many facts in geology and has become independently appreciated.

General Conclusion.—We have thus arrived at the conception that igneous eruption, since the beginning of Keewatin time, has been due to the interactions of the basaltic substratum on the overlying acid shell and sedimentary shell of the earth. The succeeding chapters are concerned directly or indirectly with the nature of these interactions. As their analysis leads to detailed comparison with the facts of geology and petrography, the sequel may be regarded as a long statement of the supreme test—the test of prophecy—which should be applied to the theory of a stratified crust and a basaltic substratum.

CHAPTER IX

ABYSSAL INJECTION

Introduction.—We have seen that rocks belonging to the gabbro clan are always exotic where they are found among the other visible rocks of the earth's crust. By no conceivable process of fusion in place can ordinary sedimentary or gneissic material be transformed into basaltic magma. Adopting the generally accepted view, such magma is to be regarded as due to eruption from the invisible interior of the earth. The mean thermal gradient determined by borings makes it equally clear that molten magma must originate at a depth of many miles. Assuming the average increase of temperature to be 3° C. per 100 meters of descent from the earth's surface, the temperature of thoroughly fluid basalt (1200° C.) is reached at the depth of 40 kilometers (about 25 miles). There is little reason to doubt that that depth is nearly the minimum for the basaltic magma before eruption. Since the thermal gradient has nearly the same average steepness in all the continents, magmatic temperatures are likely to be found everywhere at the depth of 40 kilometers or more. Hence, so far as visible rock formations are concerned, visible basaltic rock or magma must have been driven up through fissures in the earth's crust. Such fissures must now be at least 30 kilometers high and for much or all of recorded geological time they must have been at least 15 kilometers high. In a word, all visible basaltic eruptives, whether extrusive or intrusive, are best interpreted as due to *abyssal injection* of substratum material along *abyssal fissures* in the crust.

Belief in this important principle is impelled by facts and is independent of hypothesis. But to appreciate its full bearing on petrogenesis an explanation of abyssal injection must be found, and that necessarily involves speculation.

In 1906 the writer published a paper which attempted to outline the conditions for abyssal injection, on the prevailing assumption that the earth is, and has long been, a contracting body.[1]

In 1909 Johnston-Lavis issued a paper embodying an independent explanation of volcanic action on the same basis though it does not discuss some of the fundamental features of the hypothesis. It was

[1] Amer. Jour. Science, Vol. 22, 1906, pp. 195–216.

an amplification of a note published in 1890, which was first discovered by the present writer in 1910.[1]

Extracts from the writer's 1906 paper will serve to lay the elements of the speculation before the reader. However, before entering on those considerations, it is expedient to refer to the bearing of the researches carried out on the radioactivity of rock matter during the years elapsed since 1906. Moreover, the quite recent epoch-making experiments of Adams on the strength of rock under conditions of cubic compression (published in 1912) are of exceptional importance in this connection; they will be noted in the appropriate place.

Strutt, Joly, and others have proved so much radioactivity in all the types of rocks at the earth's surface that this planet must be regarded as a true, very efficient furnace, if the average content of radioactive matter also characterizes the rock matter in great depth. That is, the earth's outer shell must be growing warmer. The fact that traditional geology has demanded a cooling earth led Strutt to postulate a concentration of the radioactive matter very close to the actual surface, and Chamberlin has recently explained such a concentration in terms of the planetesimal hypothesis.[2] Some geologists are wisely withholding assent to Strutt's hypothesis. Though the break-up of radium seems not to be inhibited by increase of temperature or of pressure, or of both simultaneously (?), it is not yet proved that the break-up of the parent uranium proceeds independently of pressure and temperature. The "half-value period" of radium is only about 1300 years, while for uranium it is a billion years or more. If, then, the subsurface conditions in the earth do prevent the spontaneous disintegration of uranium, the earth cannot be a furnace "fired" by radioactivity. Until the physicists make clear the proof that the imagined stream of energy is not thus dammed at the fountain-head, geologists may well receive with caution the published statements regarding the relation of radioaction to the earth's thermal gradient.

Contraction of the Earth.—In what follows it is assumed that the earth is contracting, as so clearly suggested by structural geology. Loss of terrestrial heat is only one of several causes for the contraction. However the materials composing this plant were assembled, it is in the highest degree improbable that they have been in chemical equilibrium ever since pre-Cambrian time. Their slow rearrangement, to form compounds that are stable under the conditions of high pressure in the earth's interior, involves net decrease of volume. From this

[1] H. J. Johnston-Lavis, Geol. Mag., Vol. 6, 1909, pp. 433–442; ibid., Vol. 7, 1890, pp. 246–249.

[2] T. C. Chamberlin, Jour. Geology, Vol. 19, 1911, p. 692.

cause alone the globe may be shrinking although its mean temperature should be actually rising.

Secondly, allowance must be made for the considerable alterations of volume involved in changes of state. Crystallization of earth magma represents only one of these changes. Bridgman's experiments are showing that many substances besides water have, respectively, several polymorphic solid forms at varying high pressures. The transformation of one of these forms into another, due to appropriate shifts of pressure or temperature, is accompanied by notable volume changes. Are there similar phase changes in the silicates and metals of the earth's interior?

Again, actual field observations suggest that, at moderate depth, granite, which has crystallized from magma with the usual massive structure, may not be stable under conditions of permanent one-sided pressure. It is then changed into micaceous orthogneiss of density greater than that of the original rock. This transformation is familiar as a product of dynamic metamorphism, but it may be indefinitely more important as a product of static metamorphism, namely, that caused by the dead weight of the rocks overlying a mass of new granite or other crystalline mass. The quantitative value of such secular volume changes is exemplified in the 16 per cent. of net shrinkage involved when orthoclase passes over to muscovite and quartz.[1] The writer has come to the conclusion that, for geophysics if not also for geology, the effects of static metamorphism may very greatly transcend those of dynamic metamorphism.

It is seen that the "contraction theory" of the earth is a quite different thing from the "thermal-contraction theory," which has been so much discounted in late years. The net volume change of this planet since the early pre-Cambrian is possibly a hundred times greater than that due merely to the loss of heat during that long era.

Shells of Compression and Tension

Whether the earth, as it cools and contracts, be solid and highly rigid throughout, or whether it consist of a solid crust with an underlying fluid substratum, it is generally held by geologists that there is a "level of no strain" beneath the surface. The depth of this level has been computed for a solid earth by Davison and Darwin, who have made various assumptions which are more or less reasonable provided the fact of complete solidity is established. Their estimates for the

[1] Cf. R. A. Daly, Summary Report, Geol. Survey of Canada, 1911, p. 168.

depth of the zero-strain level vary from 2 miles to 8 miles.[1] With analogous assumptions Fisher has calculated that there will similarly be a level of zero-strain in a crust overlying the fluid substratum of a globe solidifying from the circumference inward. He found that "if the time elapsed since a crust began to be formed has been 100 million years, the depth of the level of no strain at the present time will be about 4 miles."[2] In any case the depth increases very slowly with the time elapsed since the crust first formed.

Rudski has pointed out that, if the earth's initial temperature were not uniform, the level of no strain would, in a given time be deeper than by the amount calculated on the assumptions of Davison.[3] It is, in truth, probable that the initial temperature increased downward. There are grave reasons for doubting the conclusion of Kelvin that an initial uniform temperature was secured through the foundering of early crusts. Like the suggestion of Le Conte, that this thermal state might be secured through convection currents, Kelvin's idea is not acceptable to those who hold the very probable view that the earth's internal density increases downward, not only because of increasing pressure but because of differences in chemical composition as well.[4]

It may be noted that, in the above-mentioned calculations, no account has been taken of the special and important contractions characterizing the passage of lava from the liquid to the solid state nor for polymorphic and chemical transformations, nor, except in the case of Fisher's estimates, for the fact that, with a given fall of temperature, liquid lava (diabase) contracts about twice as much as solid lava.[5]

All of these calculations have been made on the supposition that the thermometric conductivity of the material of the earth is a constant quantity. It is, however, practically certain that this conductivity decreases with rise of temperature and very greatly increases on the passage of liquid magma into solid rock.

Quantitative studies on the conductivity of rock-matter at different temperatures, in different states of compression, and in the two states of aggregation, are clearly needed. Until these are made it remains impossible to calculate the exact position of the level of no strain in the earth's crust. Nevertheless, in an earth composed of a crust floating

[1] C. Davison, Phil. Trans. Roy. Soc. London, Vol. 178A, 1887, p. 231; G. H. Darwin, ibid., p. 242; C. Davison, Proc. Roy. Soc. London, Vol. 55, 1894, p. 141. Cf. M. Reade, Origin of Mountain Ranges, London, 1886, p. 121.

[2] O. Fisher, Physics of the Earth's Crust, London, 2nd ed., 1891, Appendix, p. 45.

[3] M. M. P. Rudski, Phil. Mag., Vol. 34, 1892, p. 299.

[4] Cf. J. Le Conte, Amer. Geol., Vol. 4, 1889, p. 43.

[5] C. Barus, Bull. 103, U. S. Geol. Survey, 1893.

on a substratum which, because it is fluid and hot, has a lower conductivity than the solid, cool crust, we might expect the level of no strain to be well within the crust, even if the initial temperature gradient were comparable to that now observed in the earth's superficial shell. In a personal letter to the writer, the Rev. Osmond Fisher states that, with a liquid interior, there must be a level of no strain in the crust; and this is apparently true no matter what the initial temperature may have been. He states, further, that "the level of no strain would be the same whatever the conductivity; but the time would not be the same. The position of the level would not fall so rapidly if the conductivity were less."

The shell above the zero-strain level is under tangential compression. The shells under that level, for a considerable distance downward, are under tension. On account of the weight of all overlying shells any shell below the zero-strain level tends to be stretched or (using Reade's term) to suffer "compressive extension." This tendency increases with depth to a maximum in a level computed by Davison for a solid earth to lie 72 miles below the surface. The corresponding level for an earth with a fluid substratum has been calculated by Fisher to lie at a depth of from 30 to 55 miles, depending among other conditions on the temperature of solidification.

Beneath the surface shell of tangential compression, the rate of secular cooling and contraction and the consequent tension increase from the level of no strain downward all the way to the substratum. In his first paper Davison calculates that the average rending stress in the lower shell is, after a given time (if there be no relief by stretching or by cracking), four times the average compressive stress in the upper shell. So long as folding or overthrusting of the shell of compression does not occur, the two shells are in physical continuity and are strongly bound together.

Secular Accumulation of Tensions and of Cooling Cracks.—It is generally agreed that, on the contraction theory of mountain-building, orogenic folding and crumpling is possible through the secular accumulation of compressive stresses in the outer shell. The crucial question has not yet been satisfactorily answered as to whether there may be similarly a secular accumulation of tension and of its effects in the inner shell of the crust. If the earth's surface layer were a fluid of only moderately high viscosity, the accumulation of tension would be impossible to any sensible extent; moreover, its own weight would necessarily close all cavities almost as fast as formed during the slow secular cooling. But the average rock of the crust is a true solid known to have a very low modulus of plasticity. Pfaff has, indeed, denied even the smallest measure of true plasticity to the average crust-rock, and his experiments, like those of Adams, prove that massive granite, gneiss, or gabbro would, at surface temperatures, not flow under the weight of even 25 miles of overlying rock.[1] They would rupture and shear, but the deformation would not reach the perfection of the molecular shearing implied in true flow.

A vertical crack due to cooling contraction would thus tend to be partly closed by shearing-in of masses from its walls. The shear-planes would be inclined to the vertical. Each partial bridging of the crack makes further shearing and closing of the crack more and more difficult. A greater weight of crust would now be required since some support of the load is formed through the local meeting of the solid walls. The simple vertical stress becomes partially resolved into a complex network of oblique stresses tending to balance each other in the loci of lateral support (the principle of the arch!). The portions of the crack occurring between these loci of support may remain open because of the diminished shearing stresses along the still gaping walls. It thus appears that, though all rocks which are not laterally supported will rupture under the weight of 6 miles of crust, yet the complete closing of cracks at the same temperatures would not be expected even under the weight of a much greater thickness of crust. The depth of the shell ("zone") of fracture has been deduced from the crushing tests of stone and from the brilliant experiments of Adams and Nicolson on the deformation of marble enclosed in steel collars. The former tests evidently do not prove anything at all definite as to the pressures required to produce true plastic flow. The flow of marble under confinement has been produced under relatively low pressures, but this is a special phenomenon, the result of movement on gliding planes. A pen-knife and a few pounds of pressure will cause "flow" in a crystal of calcite. It is safe to say that similar conditions are not found in the average rock of the crust; if it flows at all the mechanism of the flow must be something entirely different.

Deformation within the shell of tension is not to be estimated simply by the ultimate strength of surface rock deformed in the laboratory. The experiments of Spring, Hallock, and others show that the rigidity of a solid increases with pressures ranging up to those about twice that borne by our substratum.[2] This experimental law strengthens the belief that cavities may remain open in the shell of tension. On the other hand, the downward increase of temperature tends to lower the internal friction and thus to promote the closing of cavities. A com-

[1] See F. D. Adams and J. T. Nicolson, Phil. Trans. Roy. Soc. London, Vol. 195, 1901, p. 367; F. D. Adams, Jour. Geology, Vol. 20, 1912, p. 97.

[2] For references see review by C. F. Tolman, Jr., Jour. Geology, Vol. 6, 1898, p. 323.

parison of the pressure-gradient (1 atmosphere to about 3.7 meters of descent) with the temperature gradient (1° C. to about 30 meters of descent) suggests the possibility that rigidity actually increases through the shell of tension down to its bottom layer, where, on account of the high temperature, the change of state, from solid to liquid, is approached; in that layer cavities are doubtless impossible.

A further indication that cavities may remain open in the shell of tension is indirect but none the less noteworthy. According to the assumption generally held by those adopting the contraction theory of mountain-building, the shell of tangential compression, free of load and unconfined as it is along its upper surface, can nevertheless for long periods of time endure without deformation a compressive stress perhaps several times greater than the weight of 5 miles of rock. It is the release of this pressure (which was *not* relieved by simple radial flow and thickening of the shell) that has led to the paroxysmal growth of a mountain range. If the outer shell can long withstand such pressures, it is reasonable to believe that the material of most of the shell of tension is not perfectly plastic under the weight of overlying crust—a pressure which is great but, in general, is only a fraction of the accumulated tangential stress of compression.

The last four paragraphs are taken from the writer's 1906 paper. Since it was published, noteworthy corroboration of the conclusion there stated has been furnished by Bridgman, Adams, and King. Telling experiments by the first two investigators mentioned have been described in the foregoing chapter (page 172). Indicating the results of his superb experiments, Adams writes as follows:[1]

"1. The calculations which have been made as to the depth below the earth's surface at which all cavities in the earth's crust would be closed by plastic flow, based on the crushing strength of rocks at the surface of the earth, are erroneous.

"2. At ordinary temperatures but under the conditions of hydrostatic pressure or cubic compression which exist within the earth's crust, granite will sustain a load of nearly 100 tons to the square inch, that is to say, a load rather more than seven times as great as that which will crush it at the surface of the earth under the conditions of the usual laboratory test.

"3. Under the conditions of pressure and temperature which are believed to obtain within the earth's crust, empty cavities may exist in granite to a depth of at least 11 miles. These may extend to still greater depths, and, if filled with water, gas or vapor, will certainly do so, owing to the pressure exerted by such fluids or gases upon the inner surfaces of such cavities or fissures."

King's mathematical discussion of these experiments led to the following conclusion:

[1] F. D. Adams, Jour. Geology, Vol. 20, 1912, pp. 97–118.

"It is also shown that as far as hydrostatic pressure in the earth's crust is concerned a small cavity at ordinary temperatures will remain open provided the depth does not exceed a value between 17.2 and 20.9 miles. At a temperature of 550° C., supposed to exist 11 miles below the earth's surface, cavities will remain open when submitted to considerably greater pressures than are found at this depth. These values greatly exceed previous estimates because experiment shows that a much higher value of limiting stress-difference than that usually employed must be taken in the neighborhood of small cavities.

"The *size* of a cavity which can exist at a given depth depends on considerations of *stability* and would demand a separate investigation."[1]

The unique value of Adams's experiments consists especially in the proof that an elevation of temperature, even to a point approaching dull-red heat, does not annul the effect of high pressure on the strength of rock.

Hence it is all the more probable that discontinuous cracks produced by secular cooling in the shell of tension should not be closed by the dead weight of the overlying shell of compression.

This part of the argument may now be summarized. On the whole it seems probable that a percentage of the whole tension developed in the lower shell through secular cooling remains, at any time previous to mountain building, unrelieved by the stretching or cracking of that shell. The development of tensional stress and the multiplication of cooling cracks will be at a maximum at some level near the middle of the shell of tension. The accumulation of compressive stresses in the outer shell will be relieved to a certain extent by recrystallization, leading to the formation of denser minerals in the shell; but geological observation shows that, in a long period of time, enormous compressive stresses are always stored until relieved by a more catastrophic process. The accumulation of the tensile stresses in the lower shell will be in some direct proportion to the degree in which relief is withheld in the shell of compression. Beneath a crust so diversely stressed, there is a compressed elastic fluid which is ready, with relative suddenness and with prodigious force, to inject itself into the shell of tension as soon as there is any local relief of pressure or any breaking of the continuity of the shell.

The whole system is evidently in unstable equilibrium. If each shell were of uniform thickness and composition, and if there were no external forces acting on the system, it would be difficult to forecast when or where the stresses could be relieved.

Injection of Magma into the Shell of Tension.—But the earth's crust is not perfectly homogeneous; none of its shells is of perfectly

[1] L. V. King, Jour. Geology, Vol. 20, 1912, p. 137.

uniform thickness; and, thirdly, there are external forces acting on the shell of tension. Of special importance is tidal stress. Slight as may be the effect of a single tidal period, for example, it will, in certain lines appropriately oblique to the earth's equator, tend to wrench apart the crust even down through its viscous bottom layer. To such a powerful fluid as that composing the substratum, this viscous layer, suddenly sheared or broken, is relatively a solid mass; to the searching fluid a plane of shearing in the viscous layer is virtually a crack. Into that plane the tidal pulsations will pump the fluid, which instantly exerts

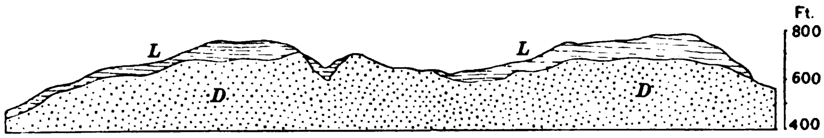


FIG. 110.—Section along the course of the Cleveland dike, Yorkshire. (After A. Geikie, Ancient Volcanoes of Great Britain, Vol. 2, 1879, p. 148; original by G. Barrow.) *L*, Liassic sediments; *D*, dike. Base of section, 400 ft. above sea level. Horizontal scale, 1:29,000.

its lateral hydrostatic and expansional pressures on a shell already prone to recoil because of the real though mild tension residual in the bottom of the shell. As the fluid thus works its way upward, it encounters rock which is increasingly more rigid and increasingly charged with accumulated tension and cooling cracks. In fact, if we conceive that the viscous bottom layer is once completely penetrated, it is easy to believe that the abyssal dike will be rapidly injected toward the top of the shell of tension. The shearing-in of the solid rock opposes the con-

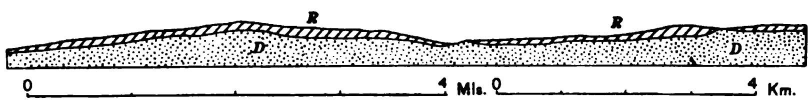


FIG. 111.—Section along the course of the Cleveland dike, across the Cross Fell escarpment. (Same ref. as for Fig. 110, p. 150.) *R*, roof rock; *D*, dike.

tinued opening of the potential fissure, but this shearing, as the level of no strain is approached, becomes slower and slower and thus more and more powerless to check the rapidly acting wedge of expanding fluid.

There are some field indications that the ascensive force of erupting magma is of the same order of magnitude as that of the weight of the earth's crust (solid shell overlying the substratum). Even the greatest lava flows are minute when compared with the earth as a whole or with any one of its primary shells. Very many, perhaps most, dikes have not reached the surface, though their terminations approach it nearly.

A good example, demonstrated during long-continued mining, is found in the famous Cleveland dike of northern England (Figs. 110 and 111). Such facts suggest that magmatic eruption is, in the first instance, a hydrostatic phenomenon, though, as further noted in Chapter XIII, other subsidiary factors are involved.

Relief of Tensions through Abyssal Injection.—On account of the strong compression at the earth's surface, the magma of the abyssally-injected wedges will not in most cases reach the surface. The act of injection produces a great change in the conditions of equilibrium in the shell of tension and therewith in the whole crust.

Fig. 112 represents a sectional view of the system after injection, the earth's curvature being neglected and the wedge being shown in

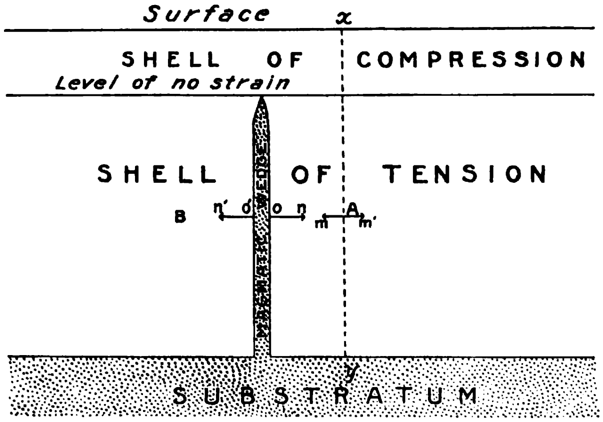


FIG. 112.—Diagram illustrating abyssal injection.

cross-section. The level of no strain is represented as about 5 miles below the surface—a depth somewhat greater than the maximum calculated by Fisher. The principle of the following argument is not affected if the depth should be a fraction of 1 mile or as much as 6 or even more miles.

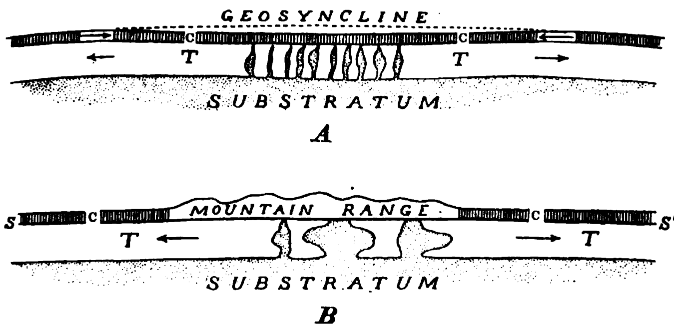
A is a particle of the crust within the solid shell of tension. In the stretching of the shell such a particle must move not only radially toward the earth's center, but tangentially as well. If the shell is homogeneous, the weight of the overlying crust will tend to shear the particle indifferently toward *m* or *m′* or toward any one of an infinite number of other points lying in the circumference of a horizontal circle described about the vertical passing through *A* and with radius *Am*. The shear-movement of particle *A* is, however, strictly controlled in direction so soon as a liquid wedge is injected. At the level of *A* the point *o* in the wall of such a wedge bears a combined hydrostatic and elastic pressure from the magma. The former pressure is sensibly equal to the weight of the column of rock Ax; the maximum elastic pressure equals the weight of the column Ay. The total of these pressures, represented by the line *on*, is equal to the oppositely directed force $o'n'$ on the wall of the wedge. *On* is not only a positive force compressing the matter between o and A; it is also, and yet more significantly, a *directive* force which determines the direction in which particle A must move as it is affected by the tensional pull of secular cooling and by shear during the compressive extension (stretching) of the shell of tension. As long as the wedge remains fluid, particle A will move in the direction of the arrow Am'. The condensation of matter, which before the wedge injection had been only potential (being due to the accumulation of tensions and cracks in the shell), now becomes actual. As particle A is forced toward m', a neighboring particle, A_1, on the same level and to the right hand of A, is similarly brought under pressure and moved in the direction of the arrow Am'. A_1 communicates its motion to A_2 and so on. The pressure at o is thus felt within the shell as far away from the wedge as the relief of the accumulated tension and the closing of cooling cracks can take place.

The movement of the particles A, A_1, A_2, etc., is analogous to that of a railway engine pushing down a train of cars which had been standing on a grade with each coupling pin at full length because of the grade. Buffer meets buffer, communicating the pressure of the engine. If the train had been nicely poised, just ready to move before the pressure was applied, and if the grade were indefinitely long, a small pressure would set in motion a train of indefinite length. The analogy is not perfect since the creep of the particles in the shell of tension is not free but is controlled by internal friction and by the strong adhesion between the shells of compression and tension. Nevertheless, it is not difficult to believe that lateral creep would be set up at a distance perhaps several times the thickness of the whole crust.

Since the conditions are precisely the same for particles B, B_1 (to the left of B), B_2, etc., there will be similar creep on the side of the wedge opposite to A in the direction of the arrow $o'n'$. The wedge is thereby widened. The continued injection of new fluid magma makes this new system of motions self-perpetuating until the attainable relief of tensions and closure of cracks is accomplished.

Thereafter, two possibilities are open. The now much widened wedge may have lost sufficient heat to solidify. The system of directed creeps or lateral movements will then be exchanged for an undirected compressive extension similar to that which prevailed before the injection. Or, if the wedge remains fluid, it will cause an indefinite continuance of lateral creep keeping pace with the differential cooling contractions in the shell of tension. In the former case, the injection of a second and of yet later wedges is possible, and their net effects, provided these wedges are elongated in the same general earth-zone,[1] are additive to those of the first wedge. Tidal or other torsion may locate such a zone of special igneous injection.

Downwarping of the Surface as a Result of Abyssal Injection.—We have seen that lateral creep will be fastest somewhere near the middle level of the shell of tension, because it is there that the defect of condensation of matter, shown in cooling crack and in residual tension, is at a maximum. The ensuing condensation of matter in the shell is



FIG, 113.—*A*, Diagrammatic section showing the relation of abyssal injection to geosynclinal downwarping. *C*, earth-shell of compression; *T*, earth-shell of tension; broken line shows position of the surface before the downwarping. *B*, Diagrammatic section showing the relation of abyssal injection to orogeny. Symbols as in *A*, with addition of *S–S'*, shear-surface of the mountain building. Igneous bodies injected and crystallized before this deformation are not shown. New, large batholiths, of slightly different ages, are indicated by stippling.

at a maximum in the immediate vicinity of the zone of injection and gradually decreases to each side of the zone. Since the two shells are still solidly knit together, the enforced creep of matter to right and left of the great wedges involves a strong downward pull exerted on the shell of compression. A downwarp of the earth's surface is thus established. The initial downwarp is of length, breadth, and depth dependent on the magnitude of the injected body or bodies. Where the injection is on a large scale the downwarp may be of geosynclinal dimensions (Fig. 113, *A*).

The down warping implies, however, that the former nice balance of stresses in the zone of compression is destroyed. Those stresses will henceforth tend directly to increase the downwarp. Sedimentation within the downwarp increases the weight on the creeping material

[1] "Zone" here means a surface belt.

of the shell of tension, which is also now beginning to feel a small downward pressure, a component of the total thrust of the bent shell of compression. The downwarping of the surface may thus gradually increase even after all magmatic injections in the zone of tension have frozen solid.

Here we may pause to apply an obvious test to the speculative reasoning so far outlined. Though magmas must have difficulty in forcing their way through the shell of compression, we should still expect that molten material would occasionally penetrate that shell, so that areas of geosynclinal sedimentation would be zones specially characterized by contemporary vulcanism. The following table (IX) illustrates the actual facts determined for the better known geosynclinals.

TABLE IX.—ILLUSTRATIONS OF VOLCANIC ACTION CONTEMPORANEOUS WITH GEOSYNCLINAL SEDIMENTATION

1. *Lower Huronian*, North of Lake Huron. (W. E. Logan, Geology of Canada, 1863, p. 55.)
   Measured section of 18,000 feet of bedded rocks, with greenstone (often amygdaloidal) at seven horizons.
2. *Animikie* (*Upper Huronian*), Lake Superior District.
   Thick metargillites and quartzites, with interbedded extrusives at various horizons.
3. *Keweenawan*, Lake Superior District. (W. C. Gordon, Mon. 52, U. S. Geol. Survey, 1911, p. 384.)
   Thick sandstones, shales, and conglomerates, with extrusives at many horizons.
4. *Shuswap Terrane* (*pre-Cambrian*), Southern British Columbia. (R. A. Daly, Summary Rep. Geol. Survey of Canada for 1911, p. 167.)
   At least 20,000 feet of limestones, altered argillites, quartzites, etc., with basic volcanics at several horizons.
5. *Grand Canyon Series* (*pre-Cambrian*), Arizona. (C. D. Walcott.)

Chuar	sediments	5,120 feet.
Unkar	sediments	475 feet.
	lavas and sediments	800 feet.
	sediments	5,475 feet.
		11,870 feet.

6. *Periods of Contemporaneous Vulcanism during deposition of the Appalachian Geosynclinal:*

Period	Region
Carboniferous	Nova Scotia; Boston district.
Silurian	Nova Scotia; Fox Islands, Maine.
Ordovician	Cobequid Mts., Nova Scotia.
Post-Cambrian and pre-Carboniferous	Boston district.

7. *Rocky Mountain Geosynclinal at the 49th Parallel.* (R. A. Daly, Memoir No. 38, Geol. Survey of Canada, 1912, p. 161.)
Measured section of more than 25,000 feet of Beltian and Cambrian sediments, with five horizons of extrusive basalt and basic andesite.
8. *Main Pacific Geosynclinal (compound)*, Alaska to California.
Repeated extrusion of basaltic and allied magmas during prolonged sedimentation in each of the Pennsylvanian, Triassic, and Jurassic periods. In California measured sections showing 15,000 to 20,000 feet of bedded rocks, including extrusives at five horizons.
9. *Cretaceous Geosynclinal in Cascade Range, 49th Parallel.* (R. A. Daly, Memoir No. 38, Geol. Survey of Canada, 1912, p. 481.)
About 29,000 feet of sandstones, argillites, and conglomerates, overlying 1400 feet of andesitic breccia.
10. *Cretaceous Geosynclinal of Vancouver Island.* (G. M. Dawson.) Sediments 13,000 feet thick, with pyroclastics near the base.
11. *Tertiary Geosynclinal of Central Washington.* (G. O. Smith.)

Period	Formation	Maximum Thickness in Feet
Miocene.	Ellensburg sediments	....
	Kecheelus andesite (extrusive)	4,000
	Yakima basalt	2,000+
	Guye sediments	3,500
	Taneum andesite (extrusive)	1,000
	Unconformity	
Eocene.	Roslyn sediments	3,000
	Teanaway basalt	4,000
	Kachess rhyolite	2,000
	Swauk sediments	5,000

12. *Three British Geosynclinals:*

	Measured Thickness in Feet	Horizons of Contemporary Vulcanism
A. *Upper Paleozoic:*		
Coal measures	8,000	
Millstone grit	5,500	
Carboniferous limestone series	4,500	Basaltic flows.
	18,000	
Unconformity		
B. *Mid-Paleozoic:*		
Old Red sandstone	10,000–12,000	Extrusive basalt, etc., at various horizons.
Wenlock and Ludlow	2,840– 3,480	
......	....	Volcanic band.
Tarannon and Woolhope	1,150– 1,650	
......	....	Volcanic band.
Llandovery	1,400– 2,300	
	15,390–19,430	

	Unconformity	
C. *Lower Paleozoic:*		
Ordovician ("Lower Silurian")	10,000+	Lavas at three chief horizons.
Cambrian	12,000+	Extrusive basalts and andesites at base.
	22,000+	

13. *Witwatersrand Geosynclinal*, South Africa. (F. H. Hatch and G. S. Corstorphine, The Geology of South Africa, 1905, p. 137.)
Witwatersrand series shows 20,000 feet of thickness, with surface flows of diabase at intervals.

14. *Geosynclinals of New South Wales.* (C. A. Süssmilch, Introduction to the Geology of New South Wales, Sydney, 1911.)

Age of Series	Sediments	Contemporaneous Volcanics	Thickness (Max.), Feet
Permo-Carboniferous.	Sandstone, shale, conglomerate, coal.	Lavas and tuffs.	17,700
Upper Carboniferous.	Sandstone, shale, conglomerate, limestone.	Ditto.	19,000
	Unconformity		
Devonian.	Shale, sandstone, limestone, etc.	Lavas and tuffs at many horizons.	31,000
Silurian.	Ditto.	Ditto.	10,000(?)
Ordovician.	Slates, shales, quartzites.	Tuffs.	"Thick."

Orogenic Effects.—By the development of a geosynclinal downwarp, the shell of compression is weakened, as experimentally illustrated by Willis in his memoir on mountain-building.[1] The weakening is most felt in the two lines where the down-warped surface parts from the spheroidal curve of the earth. If sediment accumulates to the depth of many thousands of feet in a geosynclinal, the material of the original shell of compression is softened by the rising of the isogeotherms, while the strength of the new shell of compression occupied by the sediments is low because of the poor consolidation of this new formation. For a double reason, therefore, a broad zone of weakness in the shell of compression is developed over the zone of igneous injection. Sooner or later the secular accumulation of compressive stresses will express itself in the orogenic collapse of the shell; the building of an alpine mountain range is begun.

Renewed Abyssal Injection during or after Mountain Building; Development of Batholiths.—The extent to which shortening of the transverse axes of the world's mountain ranges has occurred shows that each orogenic revolution has been accompanied by a wholesale

[1] B. Willis, 13th Ann. Rep., U. S. Geol. Surv., 1893, p. 217.

shearing of the shell of compression over the shell of tension. The surface of shear is probably not far from the level of no strain.

One effect of the shearing, faulting, and crumpling may be to squeeze small bodies of magma up into the upper shell. But the grandest results of igneous intrusion would be felt in the shell of tension. The instant that the two shells are sheared asunder, the tensions that have been accumulated because of the solid continuity of the two shells, and are still residual after the preceding injection of magma, are relieved. The shell of tension is henceforth free to contract on itself. A fluid wedge now injected into this shell, or a wedge injected previous to the shearing but still fluid, would tend, according to the process already described and especially because of the energetic, spontaneous retreat of the country rock on either side, to enlarge itself. Opposed to the active retreat and enforced creep of the solid rock of the shell away from the middle plane of the wedge and thus to the ready contraction of the shell, is the friction developed at the surface of shear. Since the shear is directed tangentially with respect to the curve of the earth, the strength of the friction is measured directly by the weight of the shell above the shear-surface. At the upper extremity of a wedge which reaches exactly to the shear-surface, the hydrostatic pressure exerted on the wall of the wedge is at least as great as the weight of the shell above the shear-surface. The magma has, in addition, the live energy of elastic expansion measured by the compression due to the weight of the whole shell of tension. The net effect of these forces is to permit of the contraction of the shell, already prone to movement on account of the sudden relief of tension, and to cause a widening of the wedge, which may assume batholithic proportions (Fig. 113, *B*). It is important to note that the recoil within the shell due to the relief of tensions will characterize the whole of the area over which the shells of tension and compression have been sheared apart; this area may be several thousand miles in diameter. The piling up of the mountain-mass above would also cause an enhanced rapidity of lateral flow in the shell of tension and likewise widen the magmatic chamber. Injection into the mountain rocks themselves would only be possible where there is local relief of compression in the now heterogeneous, unequally squeezed, and writhing mass. Since, in the nature of the case, compression generally dominates, igneous injection will, in this period, afford but small geological bodies as constituents of the range.

At the mountain-roots below the surface of shear, there are one or more great bodies of basaltic magma. As detailed in the following chapters, there are excellent reasons for believing that the acid batholiths are the product of the inevitable reactions between the primary basaltic wedges and the solid earth-crust. On account of the relief of compressive stresses in the superficial shell, these greatest of abyssal injections are free to flux or stope their way toward the surface of the earth, perhaps actually reaching it in certain cases. We shall see that visible batholiths and stocks are to be explained as the less dense gravitative differentiates from such gigantic solutions of crust-rock in the basaltic wedges.

Since it takes *time* for an abyssal wedge to work its way well up into the shell of compression, the orogenic crumpling should generally be nearly or quite completed before the visible batholithic contacts were established. In other words, batholithic intrusion to levels which can ordinarily be exposed by erosion should lag behind the crustal deformation.

Here, again, we can return to observed facts for an indication of the validity of the argument. Table VI, page 98, summarizes the leading evidence that batholithic intrusion is actually confined to orogenic belts and has probably always occurred in geological periods closely following those of mountain-building disturbance.

According to the abyssal-injection hypothesis, batholiths should be found in orogenic belts and, ideally, at or near the principal axes of those belts. The corresponding fact is reflected in the phrase "central granite," which carries a geographical truth though recalling an obsolete notion as to the cause of mountain building. Yet one cannot hold that all strongly folded mountain ranges have batholiths at their roots. The Rocky Mountains of Alberta and northern Montana, the greatly deformed western Appalachians of Georgia and Tennessee, the northern Alps of Switzerland, and the northern Carpathians are not characterized by batholiths of intrusion dates connected with the formation of these actual ranges. Each range is, in fact, celebrated for its overthrusts, which have made it unsymmetrical. Our hypothesis suggests that the batholiths connected with the deformation should be looked for on the side from which the overthrust block came. Matching the deduction, the Alberta Rockies are flanked by British Columbia batholiths of Tertiary date; the Appalachian overthrust belt, by the post-Cambrian granites of Georgia and the Carolinas; the northern Alps, by the" tonalitic zone" of Italy and the Tyrol[1] (Fig. 37). Similarly related batholiths are not visible in the Carpathians but very large masses of Tertiary acid volcanics are developed on the *inside* of the Carpathian arc.[2] One is tempted to guess that the Tertiary granite of Elba locates the original site of overthrust Apennines. The charriage of the huge block thrust from Norway over Sweden

[1] See map in de Martonne's Traité de Géographie Physique, Paris, 1909, p. 585.
[2] See V. Uhlig's Tektonische Kartenskizze der Karpathen in "Bau und Bild Oesterreichs," Vienna, 1903.

was not associated with Swedish granitic intrusion but it may have been connected with some of the greater mid-Paleozoic intrusions of central and southern Norway.

Doubtful as some of these cases may be, the agreement of fact and theory in the others is worthy of close attention. The repeated discovery of highly specialized field relations in at least three principal mountain chains must aid in establishing a final theory of the connection between magmatic movements and mountain-building.

Volcanic Action Subsequent to Mountain-building.—The larger part of visible igneous rock is intrusive. Most of the large Paleozoic and later injections have not extended to the surface. These facts suggest that the upper layer of the earth's crust has long been difficult of complete penetration by the abyssal magma. A leading cause for this relative impenetrability is the compression of the superficial shell. The stress characteristic of that shell is relieved by an orogenic paroxysm. After each paroxysm compressive stress is locally replaced or overcome through the cooling of the rocks which had been heated by shearing or by batholithic intrusion. For a double reason, therefore, the penetrability of the crust should be at a maximum in periods subsequent to strong mountain-building, especially after the solidification of batholiths associated with the disturbance. (See Frontispiece.) This expectation seems to be fairly matched by the known time relations of the greater floods of basalt, as illustrated in the following table (X).

TABLE X.—RELATION OF FISSURE ERUPTION TO MOUNTAIN-BUILDING PERIODS

Locality	Date of fissure eruption	Preceding orogenic period
Lake Superior District...	Keweenawan............	Close of the Animikie.
Rocky Mts. at 49th Parallel.	Middle Cambrian (?).....	Early Middle Cambrian (?)
British Islands..........	Devonian...............	Caledonian.
British Islands..........	Carboniferous...........	Hercynian.
Appalachian Mts........	Triassic.................	Close of Paleozoic.
British Columbia........	Triassic.................	Carboniferous.
Deccan, India...........	Cretaceous (or early Tertiary?)	Late Triassic (also later?)
Great Rift, Africa.......	Cretaceous (Kaptian series.)	Late Triassic (also later?)
Washington State.......	Eocene (Teanaway basalt)	Close of Laramie.
N. W. Scotland.........	Oligocene (Lower Miocene)	?
Iceland.................	Miocene................	?
Washington State.......	Miocene (Yakima basalt).	Post-Eocene and pre-Miocene.
Great Rift, Africa.......	Miocene (?).............	Tertiary (Alps, etc.).
Great Basin, U. S. A.....	Pliocene.................	Miocene.
Snake River, Idaho......	Pliocene.................	Late Miocene.
Hauran, Syria...........	Pliocene.................	Earlier Tertiary.
Iceland.................	Pleistocene and Recent...	Tertiary.

The effusion of a basaltic flood is usually ascribed to the mere squeezing-out of the magma from beneath a cracked and sinking earth-crust. Yet some force may also be available from the expansion of the substratum material as it rises to levels of enormously lessened pressure. This expansion is of two kinds—that of the lava regarded as bubble-free, and that of the gases separated from it in bubble form. If the expansive energy of the liquid proper is not all expended in driving asunder the walls of the injected body, some of that great force is available for extrusion. As magma nears the surface, the separation of the dissolved gas must still further increase the volume and tend to cause outflow at the surface. The relative importance of these three conditions for extrusion is by no means apparent, though the writer believes that the expansional energy of the injected *liquid* should have more attention than it has had in general treatises on igneous action.

Summary

Postulates.—The assumptions on which the foregoing hypothesis has been based are the following:

a. A contracting earth superficially composed of a relatively thin crust overlying a fluid basaltic substratum of unknown thickness.

b. The substratum so much compressed by the weight of the crust as to be probably able to float the crust.

c. Through contraction, the development of a level of no strain in the crust not far from the earth's surface.

d. The accumulation of pressure in the shell of compression and the simultaneous accumulation of cracks and of some of the powerful tension unrelieved in the shell below the level of zero-strain.

e. A steady or recurrent dislocation of the shell of tension permitting of the forceful injection of the fluid substratum, to which even the viscous layer of the shell acts as a relatively solid mass at the moment of dislocation. This dislocation has been referred to the tidal torsion of the earth's crust, but the subequatorial torsion implied in the tetrahedral theory of the earth, or crustal deformation due to the play of other cosmical forces or of forces induced by the heterogeneity of the crust, may similarly cause dislocation in the shell of tension.

Conclusions.—1. The abyssal injection involves condensation of the matter in the shell of tension. Cracks are closed and much of the accumulated tension is relieved by an enforced creep of matter away from the injected body. So long as the body remains fluid the stretching of this shell due to continued contraction of the earth is accomplished by creep of matter in the same directions. The amount of creep is at a maximum above the zone of injection and decreases to a minimum at certain distances to right and left of the middle line of the zone.

2. This lateral creep induces a downwarp of the earth's surface immediately overlying the zone of condensation. The resulting geosyncline may be the seat of prolonged sedimentation. If so, the weight of the sediment itself tends to increase the lateral creep in the shell of tension and the downwarp slowly deepens.

3. The shell of compression is already weakened at the angles of downwarp; it is further weakened by the sedimentary blanket which, comparatively little resistant itself, causes a softening of its basement through a rising of the isogeotherms. When the filling of the geosynclinal has sufficiently thickened, the shell of compression, owing to its secular accumulation of stresses (which are intensified by metasomatic changes in the shell), begins to collapse. Mountainous forms and structures result.

4. The complete shearing-apart of the shells of compression and tension during the orogenic revolution releases the tensions still unrelieved in the underlying shell. Abyssal injection on a large scale is thus initiated or continued in the shell of tension. The relief of compressive stresses in the act of building the mountains first occasions the possibility of magmatic stoping and thus of the extensive assimilation of schists and sediments by the primal basaltic magma. The differentiation of the compound magmas of assimilation may explain the batholithic central granites, etc., of mountain ranges, along with their satellitic stocks, injected bodies, and volcanic outflows.

5. The regional warpings of the earth's crust may be partly, at least, referred to the varying strengths of abyssal injection from a fluid substratum.

6. The location and alignment of mountain ranges, the location and elongation of geosynclinals, the final development of igneous batholiths and satellitic injections, are all interdependent and related to *special* zones of powerful abyssal injection from the substratum. These zones are, in the large, located by cosmical stresses affecting the earth along special azimuthal lines.

7. Mountain building causes relief of compressive stresses in the superficial shell. The surface outflow of magma, either secondary or directly derived from the substratum, may therefore be specially pronounced after an orogenic revolution. In general, the theory of vulcanism is also fundamentally affected by the doctrine of the shell of tensions which are not entirely relieved by the compressive extension of that shell.

CHAPTER X

MAGMATIC STOPING

Development of the Theory.—In 1893, Professor J. E. Wolff assigned the field problem of Mount Ascutney, Vermont, to the writer, then a student at Harvard University. It was found that the mountain was essentially made up of three typical stocks of successive intrusion periods (Fig. 64). For many years the writer was baffled in the attempt to explain the mode of intrusion of these bodies. It was not until 1902 that a reasonable hypothesis became disentangled from the mass of facts compiled from this local study and from the literature of plutonic geology. The writer thus first conceived the principle of "magmatic stoping," and "The Geology of Ascutney Mountain, Vermont," embodying a brief statement of the hypothesis, was published in 1903.[1] Simultaneously, a fuller account of it was printed in the American Journal of Science.[2] The subject was further discussed by the writer in volumes 16 (1903) and 26 (1908) of the same periodical.

In the search for other statements of the hypothesis, it was found that the central idea had independently impressed itself on Lawson and Goodchild, though neither of these authors elaborated the arguments for and against it.[3] Meantime, Barrell independently deduced a similar mechanism for the batholith at Marysville, Montana, but did not publish his results until 1907.[4] Still later (1911) the masterly work of N. V. Ussing, on the geology of the Julianehaab region, Greenland, was posthumously issued, bearing the information that its author had also invented the stoping hypothesis, during the year 1900, when at work in Greenland.

The reader is referred to the papers mentioned for much of the published evidence favoring the stoping hypothesis. To keep reasonable limits of size for this book it is necessary to omit many details of that evidence, both published and unpublished. Yet the matter is so vital to petrogenic theory that a fairly full summary of the argument will be presented. Some paragraphs of the writer's 1908 paper will here be quoted.

[1] Bull. 209, U. S. Geol. Survey, 1903, pp. 93–113.

[2] Amer. Jour. Science, Vol. 15, 1903, pp. 269–298.

[3] A. C. Lawson, Science, Vol. 3, 1896, p. 637; J. G. Goodchild, Geol. Mag., Vol. 9, 1892, p. 447, and Vol. 1, 1894, p. 22.

[4] J. Barrell, Prof. Paper No. 57, U. S. Geol. Survey, 1907, pp. 151–174.

The problem relates to the mode of intrusion for the magma of batholith or stock through the last few thousand feet of its uprise. This question is independent of any theory as to the source of the magma. In what follows it will be assumed, as a phase of our fundamental postulate, that the original magma of every post-Keewatin subjacent body has been basaltic. Even if that postulate should be

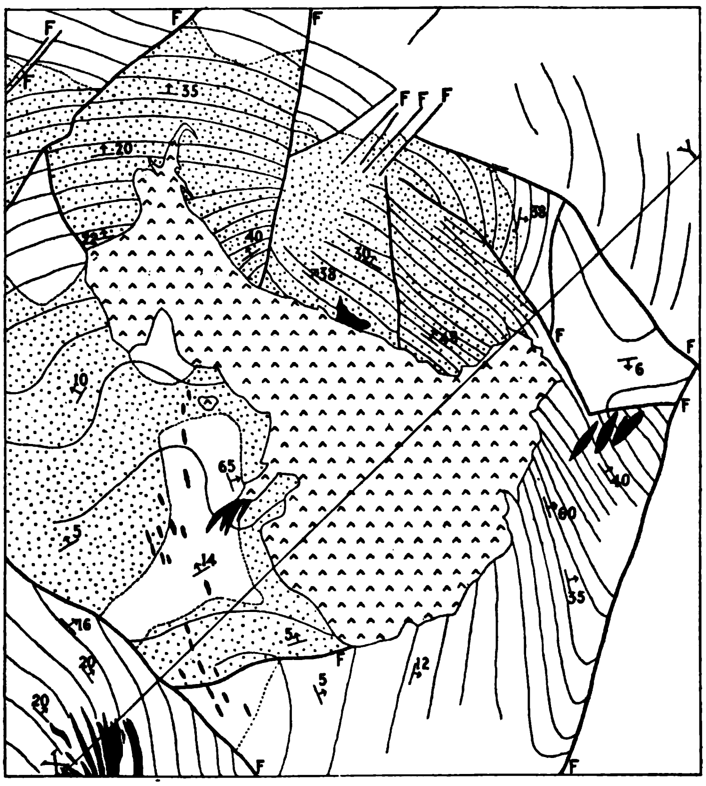


FIG. 114.—Map of the quartz diorite stock (*carets*) at Marysville, Montana. (After J. Barrell, Prof. Paper No. 57, U. S. G. S., 1907, p. 74 and map in pocket.) *Stipple*, Empire shale; *blank*, Helena limestone; *solid black*, diorite, microdiorite, and diorite porphyry; *F*, faults; dips shown in degrees; *thin lines* are strike contours with 250-ft. interval. Note cross-cutting igneous contacts and general evidence of magmatic replacement. Scale, 1:62,000.

shown to be incorrect, the strength of the stoping hypothesis would not be diminished.

A leading fact concerning subjacent bodies is their *replacement* of the invaded formations, as illustrated on pages 99 and 109. In a large batholith the rock so replaced is often seen to have covered hundreds of square miles and to have a volume to be estimated in terms of hundreds of cubic miles.

Some of the replacement may be credited to marginal assimilation, as advocated specially by the French school of petrologists. Yet this cannot be the controlling factor. Allowing everything possible for the solvent power of magmatic gases, the difficulty of imagining thermal conditions adequate to permit of the known amount of replacement through marginal assimilation alone has rightly helped to prevent general belief in this process as the dominant one. The usual lack of chemical sympathy between a subjacent body and its country rocks offers a difficulty no less great. Neither stirring by convection or other currents, nor magmatic differentiation, nor both actions together can explain these chemical contrasts, if the assimilation is wholly marginal, that is, on the roof and walls of the magmatic body.

Only one other possibility is apparent. The rock matter replaced

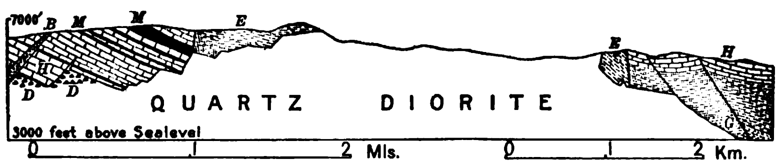


FIG. 115.—Section along the line X–Y in Fig. 114. *G*, Greyson shale; *E*, Empire shale; *H*, Helena limestone; *M*, microdiorite; *B*, Belmont diorite porphyry; *D*, diorite. Note stoping reentrants in the roof of the stock; and the peripheral position of the diorite.

must have sunk into the magma to levels well below those of the visible contacts (Figs. 114 and 115).

Recently, Clough, Maufe, and Bailey have suggested that a batholithic chamber may be formed by the sinking of a single subterranean block whose height is nearly as great as the whole thickness of the earth's crust. With the down-faulting, the chamber so formed is filled with magma which rises along the fault planes to the level of the chamber. An analogy is found in the remarkable "cauldron-subsidence" at Glen Coe, Scotland[1] (Fig. 116). This case is, however, only an analogy. It is at least possible that the sunken block at Glen Coe is merely part of the relatively thin roof of a batholith. Such partial subsidence of a roof fragment might be expected on any theory of batholithic intrusion. The existence of the "cauldron" does not compel the view that the great chamber beneath was opened by similar down-faulting *en bloc*. The authors assume that the average density of the earth's crust is greater than that of the mag-

[1] C. T. Clough, H. B. Maufe, and E. B. Bailey, Quart. Jour. Geol. Society, London, Vol. 65, 1909, p. 611.

matic substratum. This would be true if the substratum were of granitic or rhyolitic composition. It may not be true if, as assumed in the present work, the substratum is basaltic. The writer has published evidence suggesting that the earth's crust is, in fact, of lower average density than its substratum and, since Keewatin time, has been generally under conditions of stable equilibrium.[1] Without further discussing the mechanical difficulties in the way of accepting "cauldron-subsidence" as an explanation of batholithic chambers,

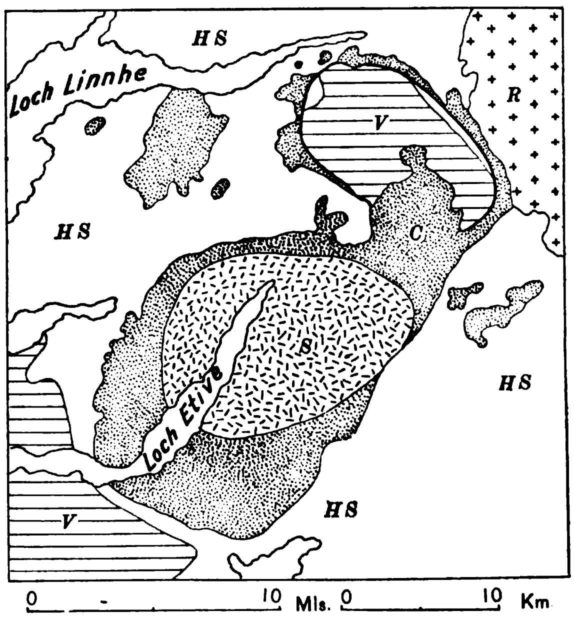


FIG. 116.—Map of the Glen Coe district, Scotland, showing location of the "cauldron-subsidence." (After C. T. Clough, H. B. Maufe, and E. B. Bailey, Quart. Jour. Geol. Soc., Vol. 65, 1909, p. 614.) *HS*, Highland schists; *V*, Glen Coe volcanics; *R*, Rannock Moor granite; *C*, Cruachan granite; *S*, Starav porphyritic granite. The heavy curved line represents the fault rim of the sunken part of the batholithic roof. The intrusives form a composite batholith.

we may assume that the authors of this interesting suggestion accept as probable the principle of magmatic stoping.[2]

The hypothesis of stoping includes the following essential points:

1. Marginal shattering of the solid rocks which form the roof and walls of the magmatic chamber.

2. Sinking of the blocks (xenoliths) produced by the shattering.

[1] R. A. Daly, Amer. Jour. Science, Vol. 22, 1906, p. 201.

[2] Op. cit., p. 665.

3. Repetition of these processes until the chamber filled with liquid magma is appreciably enlarged.

Marginal Shattering.—At the upper levels of an abyssally injected wedge the magma must have a temperature many hundreds of degrees Centigrade above the original temperatures of the country rock. At the contact the solid rock is rapidly heated to the magmatic temperature; farther away from the contact it must be heated very slowly. Rock matter is comparable to artificial glass in its thermal conductivity or diffusivity. Using the average value of the diffusivity (κ) for rock at ordinary temperatures, it is possible to calculate the temperature gradient established at the end of a given period, if the original temperature (c) of the wall-rock and the magmatic temperature (b) are assumed. It may be further assumed that the magma is of large volume and is kept stirred by currents.

If b be taken as 400° F. (corresponding to an average depth of about 24,000 feet), c as 2200° F., and κ as 400 (the value used by Kelvin), the temperatures of the wall-rock at the end of 1, 4, 16, and 100 years would have the values shown in the following table (XI) for the respective distances from the contact which are shown in the first column of figures.[1]

TABLE XI

Distance in feet	One year	Four years	Sixteen years	One hundred years
0	2200° F.	2200° F.	2200° F.	2200° F.
10	1703	1947	2074	
20	1263	1703	1947	
40	683	1263	1703	
80	408.5	683	1263	
100	ca. 400	537	1078	1703
160	400	408.5	683	
200	400	ca. 400	537	1263
320	400	400	408.5	
400	400	400	ca. 400	683

The table shows that, at the end of the first year, the temperature of the rock is but slightly affected by the magmatic heat at a point 80 feet from the contact, and that the temperature gradient for the 80-foot shell then averages nearly 23° F. per foot. At the end of four years the temperature is but slightly affected at a point 160 feet from the contact and the temperature gradient is about 11° F. per foot.

But κ cannot be nearly so great as 400 in the case before us. The conductivity k decreases rapidly with rise of temperature in rock. The experiments of Weber, Bartoli, Roberts-Austen and Rücker, and Barus

[1] See R. A. Daly, Amer. Jour. Science, Vol. 26, 1908, p. 24.

show that the specific heat of rock averages about .180 at 20° C. and increases regularly with rise of temperature, so that at 1100° C. the specific heat averages about .280.[1] It follows that thermal diffusivity in rock decreases with rising temperature even faster than the conductivity decreases.

It seems safe to assume, first, that the diffusivity of the gradually heated wall-rock may vary from 275 or less to 150 or 100; secondly, that the average diffusivity of an 80-foot shell heated during the first year by adjacent molten magma will be no greater than 200. If κ be regarded as averaging 200 for all periods greater than one year, the four columns in the table showing temperatures will serve if the times are, respectively, 2, 8, 32, and 200 years.

As a result of somewhat rigorous calculation, then, it appears certain that the heating of wall rock by plutonic magma must progress with great slowness and that the resulting temperature gradient in the shell adjoining the molten magma must be steep for many years after the original establishment of the contact.

The stresses produced in the wall rock by this differential heating must greatly transcend the strength of the rock as estimated by ordinary breaking tests. The tendency is to reproduce underground the shattering and exfoliation so often exhibited on the sills, columns, etc., of stone buildings wrapped in the flames of a city conflagration.

Again, several experimenters have shown that different rocks have different coefficients of thermal conductivity, as herewith illustrated from a recent table of Königsberger.[2]

	Absolute Conductivity ($\times 10^3$)
Simplon gneiss, highly feldspathic	5.50
Simplon gneiss, rich in biotite	6.75
Aare granite	4.03
Phyllite	6.77
Calcareous phyllite	7.30
Marble	5.20
Obsidian (Lipari)	1.92
Andesite (Orizaba)	3.06

It is well known that layered rocks conduct heat at varying rates, depending on the direction of heat flow in relation to the layering. The conductivity may be about twice as great along cleavage planes as it is across the cleavage. The flow of heat must also differ in rate as the country rock varies from point to point in its content of water.

These factors co-operate in producing great differential stresses in the wall rocks of a magmatic wedge.

[1] For references see J. H. L. Vogt, Christiania Videnskabs-Selskabets Skrifter, I. math.-naturv. Klasse, No. 1, 1904, p. 40.

[2] J. Königsberger, Neues Jahrb, für Mineralogie, etc., B. B. 31, 1911, p. 141.

Finally, additional stresses must be induced by the tension of fluids trapped in the heated contact-rock. If a cavity is entirely filled with water, the expansional force of the fluid when heated through several hundred degrees is indefinitely greater than that just sufficient to rend the rock even under conditions of cubic compression.

It seems certain, therefore, that the contact shell of the country rock must become packed with tensions. These slowly accumulate until the shell in a sense "flies to pieces," like a Rupert's drop suitably scratched.

However imperfect this explanation of contact-shattering may be, there can be no doubt as to the reality of the process. The typical batholith outcrops with an external belt of apophyses. In many cases their intrusion must have been preceded by the development of intense, inconceivably complicated stresses in the country rock (Fig. 117).

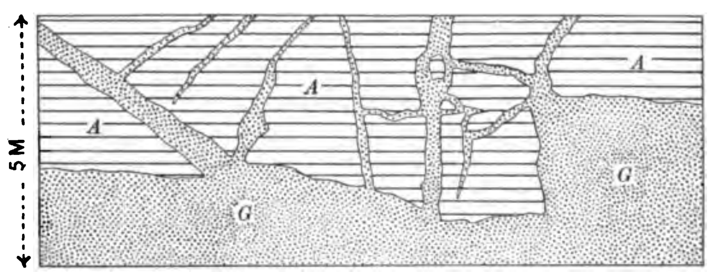


FIG. 117.—Arrested stoping at the roof of the Lausitz granite batholith, Fichtelgebirge; quarry exposure. (After R. Lepsius, Geologie von Deutschland, Teil 2, 1903, p. 194.) *A*, Andalusite-mica rock (hornfels); *G*, granite.

Many batholiths and stocks are also characterized by internal belts of inclusions of the country rocks (Fig. 118). These blocks (xenoliths) are entirely similar to many of the smaller masses separating the intrusive tongues of the outer belt, and very often no sharp line separates the two belts in their outcrop.[1] The intrusion of apophyses and the complete enclosure of the blocks in the magma are thus clearly parts of the same process.

The fact that the xenoliths have not sunk or risen in the magma far from their original niches in wall or roof shows that the magma was extremely viscous at the time of enclosure.[2] Yet the xenoliths are

[1] E. Coste has mapped an unusually good example in the Madoc district of Ontario: see Amer. Jour. Science, Vol. 16, 1903, p. 118.

[2] Some experiments by Tammann led him to conclude that the viscosity of a greatly undercooled liquid approaches that of the solid crystal of the same substance. He found a discontinuity in the temperature-viscosity curve. (G. Tammann, Zeit. phys. Chemie, Vol. 28, 1899, p. 17.)

characteristically angular and generally they are not arranged with their longer axes parallel; nor, as a rule, are the xenoliths pulled out into smears. These are considerations strongly adverse to the notion that batholiths are merely injected bodies, intruded by a forcing asunder of the invaded rocks along master fissures. On the other hand, the actual facts of the field suggest that batholithic magma has *actively* attacked its country rocks even in the very last stage of the magmatic history, when the batholith was almost frozen. With the higher temperatures and lower viscosity of the long antecedent period, the magma must certainly have had still higher activity with greater shattering power.

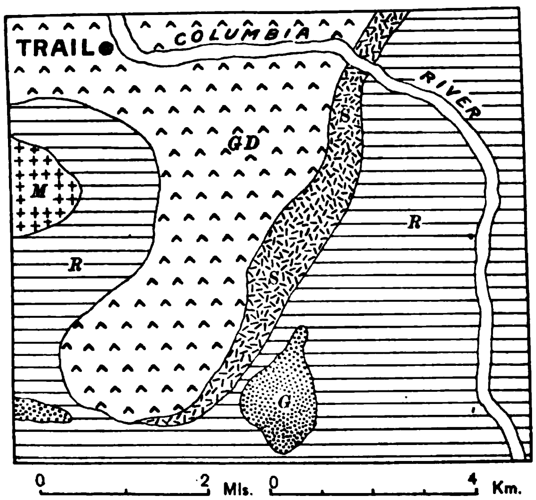


Fig. 118.—Shatter-zone (*S*) at the contact of the Trail batholith, British Columbia. (R. A. Daly, Memoir 38, Geol. Surv. Canada, 1912, p. 349, and map sheet No. 8.) *R*, Rossland volcanic series (latites, andesites, and basalts) and older formations; *M*, Rossland monzonite stock; *GD*, granodiorite batholith; *G*, alkaline biotite-granite stocks.

Further illustration of the efficiency of magmatic shattering is given in the writer's second intrusion paper.[1]

Relative Densities of Xenolith and Magma.—Will the shatter blocks sink in the basaltic magma of abyssal injection? According to experiments by Bischof, Delesse, Cossa, Joly, Douglas, and others, the glassy phase of ordinary rock is always of lower density than the

[1] Amer. Jour. Science, Vol. 16, 1903, pp. 110–125. Through the displacement of a decimal point, the writer, on page 113 of this paper, indicated a theoretical pressure of more than 1,000,000 atmospheres as due to magmatic heating in the country-rock. The calculation actually gave 10,000+ atmospheres. The general argument is not affected by this error.

holocrystalline phase at the same temperature.[1] Barus, in a series of famous experiments, has followed the density changes of basaltic glass to high temperatures.[2]

Using the best minimum values (Douglas) for the observed decreases in density with change of state, and using Barus's result for the further decrease on heating the glass, the writer has calculated the densities (at atmospheric pressure) shown in Table XII.[3]

TABLE XII

	Specific gravity of crystalline rock at:			Specific gravity of same rock when molten at:			
	20° C.	1000° C.	1300° C.	1000° C.	1100° C.	1200° C.	1300° C.
Gabbro and diorite	2.80	2.73	2.71	2.57	2.56	2.54	2.53
	2.90	2.83	2.80	2.66	2.65	2.64	2.63
	3.00	2.92	2.90	2.75	2.74	2.73	2.72
	3.10	3.02	3.00	2.84	2.83	2.81	2.80
	3.20	3.12	3.10	2.94	2.92	2.91	2.91
Quartz diorite and tonalite.	2.70	2.63	2.61	2.46	2.45	2.44	2.43
	2.80	2.73	2.71	2.54	2.53	2.51	2.51
Syenite	2.60	2.54	2.53	2.33	2.32	2.31	2.31
	2.70	2.63	2.61	2.42	2.41	2.40	2.40
	2.80	2.73	2.71	2.52	2.51	2.50	2.50
Granite and gneiss	2.60	2.54	2.52	2.31	2.30	2.29	2.29
	2.70	2.63	2.61	2.40	2.39	2.39	2.38
	2.80	2.73	2.71	2.49	2.48	2.47	2.47

Table XIII shows the changes in specific gravity undergone by blocks of stratified and schistose rocks (common country-rocks about batholiths), as these blocks, arbitrarily regarded as still solid, assume the temperature (1300° C.) of molten magma in which they are immersed.

TABLE XIII

	Range of sp. gr. at 20° C.	Range of sp. gr. at 1300° C. (solid)
Gneiss...........	2.60–2.80	2.52–2.71
Mica schist......	2.75–3.10	2.67–3.00
Sandstone........	2.20–2.75	2.13–2.67
Argillite.........	2.40–2.80	2.32–2.71
Limestone........	2.65–2.80	2.57–2.71

[1] G. Bischof, L. und J. Jahrbuch für Mineralogie, 1841, p. 565; cf. ibid., 1843, p. 1; A. Delesse, Bull. Soc. géol. France, Vol. 4, 1847, p. 1380; A. Cossa, quoted in Zirkel's Lehrbuch der Petrographie, Vol. 1, 1893, p. 681; J. Joly, Trans. Roy. Soc. Dublin, Vol. 6, 1897–98, p. 283; J. A. Douglas, Quart. Jour. Geol. Soc., Vol. 63, 1907, p. 145.

[2] C. Barus, Bull. 103, U. S. Geol. Survey, 1893.

[3] Amer. Jour. Science, Vol. 26, 1908, p. 27.

It appears from these tables that nearly all xenoliths must sink in any molten granite or syenite; most xenoliths must sink in molten quartz diorite, tonalite, or acid gabbro. Many xenoliths might float on basic gabbro but the heavier schists and gneisses must sink in even very dense gabbro magmas at 1300° C.

Giving, then, the highest permissible values to the specific gravities of magmas, it is still true that blocks, such as are shattered from the wall or roof of a batholith, must sink when immersed in most magmas at atmospheric pressure. As shown in the first intrusion paper, the blocks would likewise sink, though the magma enveloping them lies at depths of 10 or 15 kilometers below the earth's surface.

Sinking of the Shattered Blocks.—It has been objected to the stoping hypothesis that the viscosity of granitic magmas is too great to allow of the sinking of blocks even much denser than those magmas. This objection has, however, never been sustained by definite experimental or field proofs. The xenoliths visible along batholithic contacts have assuredly not sunk far from their former positions in wall or roof and the reason for this must be sought in the high viscosity of the magma. High viscosity is an essential attribute of a nearly frozen magma. The phenomena of magmatic differentiation unquestionably show that each plutonic magma must pass through a long period of mobility. The most viscous of granitic magmas, the rhyolitic, issues at the earth's surface with such fluidity that the rhyolite often covers many square miles with a single thin sheet. The absolute viscosity of the Yellowstone Park rhyolites must have been of a low order when many of these persistent flows were erupted.

Even granting that the kinetic viscosity of a plutonic magma is thousands of times that of water, it seems inevitable that it could not support xenoliths more dense than itself. In a few days or weeks stones will sink through, and corks will rise through, a mass of pitch, the viscosity of which is more than a million of millions of times that of water. Ladenburg has lately shown that small steel spheres will, in a few minutes, sink through 20 centimeters of Venetian turpentine, a substance 100,000 times as viscous as water. Ladenburg's experiments have verified Stokes's generally accepted equation expressing the rate of sinking of a sphere in a strongly viscous fluid:

$$x = \frac{2}{9} \frac{gr^2(d-d')}{v},$$

where x = the velocity of the sphere when the motion is steady; g = the acceleration of gravity; d = the density of the sphere; d' = the density of the fluid; r = the radius of the sphere; and v = the viscosity of the fluid.

Assuming that a granite magma has viscosity even as high as that of the hard pitch above mentioned, a sphere of a common type of gneiss, 2 meters in diameter, would sink more than 10 centimeters per day. A similar sphere 4 meters in diameter would sink more than 1.3 meters per day. If the sphere were much larger, the Stokes formula does not apply. Allen has developed the following formula for such very large spheres:

$$x^2 = \frac{1}{k} \cdot \frac{4\pi}{3} \cdot gr\frac{d-d'}{d},$$

in which k is a constant for a given liquid-solid system. The terminal velocity in this case varies directly as the square root of the radius.

Other things being equal, it follows that very large shatter-blocks would sink much faster than those having diameters of only 1 or 2 meters. This deduction agrees with the common observation that along granite contacts very large xenoliths are generally rare, though, of course, roof-pendants of indefinite size may there be found.

Subjacent bodies must cool with extreme slowness, both on account of the low conductivity of the country rock and of the liberation of latent heat in crystallizing. Hence the presence of xenoliths at the observed levels in these bodies must generally betoken for the liquid at the time of enclosure of the block a viscosity much higher than that of ordinary pitch. At the very close of the magmatic period the viscosity may be comparable to that of the glass in a window.

These conclusions seem valid even though the influence of pressure on magmatic viscosity is not accurately determined. The pressure due to the weight of a batholithic roof, at the close of the magmatic period, is generally to be estimated in terms of scores or hundreds of atmospheres, not thousands of atmospheres. Under such relatively low pressures, temperature must have dominant control over the mobility of the magma, that is, over its response to stress-differences. By cooling, crystallization is induced and therewith the viscosity becomes practically infinite. Such a condition was nearly approached when the visible xenoliths were enclosed in stock or batholith.

We are driven to the conclusion that xenoliths must sink rapidly in magmas of such relatively low viscosity as that permitting magmatic differentiation or the injection of off-shooting dikes. This magmatic stage is certainly of long duration for the subjacent masses, a stage so prolonged that many successive shells of roof and wall may be shattered and stoped away. If the original magma be an abyssal wedge of primary basalt, the shatter-blocks composed of the lighter rock materials might float in the pure basalt, but the heavier types would sink.[1] In general, the primary magma must become somewhat acidified and hence less dense by the solution of such blocks as well as by marginal assimilation. Stoping thus for a time becomes more and more rapid; after reaching a maximum of speed, the process reaches zero activity with the crystallization of the body.

Roof-foundering.—How far have magmas thinned the roof of their chambers by stoping? Is it possible that some batholithic roofs have, in part, been destroyed? In the first presentation of the stoping hypothesis the writer stated his belief that such foundering of surface rock has not taken place during Paleozoic or later time, but suggested it as a possibility in the early pre-Cambrian period, when the acid shell of the earth was being developed. Further consideration has caused a revision of that opinion. He has since suggested that actual roof-foundering may be represented in the rhyolitic region of the Yellowstone National Park and in the Blue Hill complex of Massachusetts.[2] Other possible examples of the process have been mentioned in Chapter VII.

Nevertheless, it is clear that roof-foundering has rarely occurred in post-Huronian time, and this fact must be reconciled with the stoping hypothesis if the latter is to be finally accepted as a true and essential part of the batholithic mechanism. Barrell speaks of this necessity as "the greatest theoretical difficulty in the way of accepting stoping as one method of batholithic invasion." He points out, however, the unescapable truth that the same problem faces every theory of such invasion.[3]

Since the Keewatin period, the earth's crust has remained essentially coherent, and through it the primary basalt has been erupted often and in many places. However, the irregular attitude of the axes of the Laurentian batholiths as well as the abundance of those bodies may possibly be explained by the repeated foundering of an earth crust which was especially thin and weak in that early epoch.

We have seen that most, if not all, of the post-Cambrian batholiths are confined to the sites of folded geosynclinals, and that such bodies are generally arranged with their longer axes parallel to the respective orogenic axes. (See pages 91 and 94.) In the last chapter this relation is explained on a genetic basis.

Thus, the intrusion history of the globe may be conceived as divisible into three epochs: the first being that in which the outer primary shell was becoming stable through successive solidifications

[1] Metamorphism at batholithic contacts will cause even argillites, with initially low densities, to assume specific gravities higher than that of molten basalt.

[2] R. A. Daly, Proc. Amer. Acad. of Arts and Sciences, Vol. 47, 1911, p. 60.

[3] J. Barrell, Prof. Paper No. 57, U. S. Geol. Survey, 1907, p. 172.

and founderings; the second being the post-Keewatin (Laurentian) epoch of very general interaction between the fluid basaltic substratum and acid crust, without extensive founderings but with development of many large, irregularly occurring batholiths; the third, a period of the localization of batholiths in certain mountain-built belts, where alone there seems, in this period, to have occurred the injection of molten magma in masses of batholithic size, in but few cases accompanied by roof-foundering.

In the third paper on the Mechanics of Igneous Intrusion, the writer briefly discussed the conditions leading to this contrast between batholithic activity in the early and later stages of earth history.[1] The final explanation may partly lie in the highly probable fact that the earth's shell of compression has been notably thickened by secular cooling during post-Laurentian time. Moreover, a special thickening of the shell above the "level of no strain" is a necessary feature of a mountain range produced by the crumpling and overthrusting of geosynclinal sediments. Conduction into roof and walls, magmatic stoping, and the attendant abyssal solution of solid rock replaced in the shell of compression, all involve the ultimate exhaustion of heat supply in a magmatic wedge. With sufficient thickening of the shell above the level of no strain, stoping must be arrested before the batholithic roof is dangerously thinned. It should be remembered that there is no danger of foundering until a part of the roof can be wholly *immersed* in the batholithic magma.

In conclusion, we seem to have reason for believing that the "problem of the cover" will find its solution. A number of conditions specially developed in Paleozoic and later times have together tended to prevent the foundering of the roofs of granitic batholiths, though perhaps without success in the case of a few of these bodies.

Stoping in Sills and Laccoliths.—The writer has published a note as to the testimony of the laccoliths on the stoping hypothesis.[2] It was pointed out that these bodies generally show negative evidence and a chief reason suggested is the high initial viscosity of these intrusive bodies. At the time of injection, a sill is believed to have been relatively much less viscous than a laccolithic mass. Hence it is somewhat significant that many sills enclose xenoliths, which because of their greater densities have doubtless fallen from the respective roofs of the sills. Cases in the Purcell sills of British Columbia, in the Pigeon Point intrusive of Minnesota, and in the Sudbury sheet of Ontario have been cited by the writer.[3]

[1] Amer. Jour. Science, Vol. 26, 1908, p. 32.
[2] R. A. Daly, Amer. Jour. Science, Vol. 15, 1903, pp. 285–286.
[3] R. A. Daly, Amer. Jour. Science, Vol. 20, 1905, pp. 194, 201, 204, 207–208.

According to Weed, shale fragments may have been stoped *up*, in the minettic magma at Yogo Canyon, Montana[1] (Fig. 119). Lewis has suggested, in connection with his valuable study of the huge diabase sill of the New Jersey Palisades, the possibility of "underhand stoping," stating that the (crystallized) diabase is 20 per cent. heavier than the enclosing strata.[2] He makes no estimate as to the density contrast of the molten diabase and the invaded sediment. The difference cannot be nearly as much as 20 per cent. In any case the dominant rocks of the earth's crust must have specific gravities higher than that of molten diabase or basalt, so that, if "underhand stoping" characterized the exceptional sheet of New Jersey, "overhand" (overhead) stoping is all the more probable in the average chamber of fluent magma.

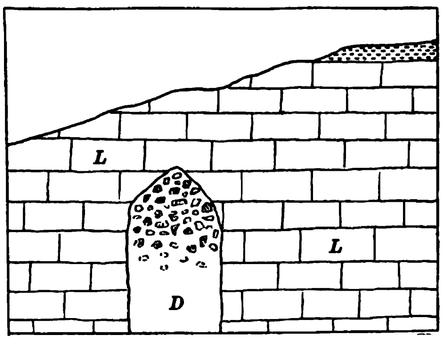


FIG. 119.—Section of top of sapphire-bearing minettic dike (3 to 6 ft. wide) in wall of Yogo canyon, Montana. (After W. H. Weed, 20th Ann. Rep. U. S. G. S., Pt. 3, 1900, p. 456.) The blocks in the dike are composed of shale and limestone. *L*, Limestone; *D*, dike. According to Weed this dike illustrates underhand stoping.

Abyssal Assimilation of Stoped Blocks.—A principal corollary of stoping is the chemical change necessitated in the invading magma. We may reasonably assume that the mass is hotter in its deep interior than at wall or roof and that solution of the sunken xenoliths took place during most of the magmatic period. If the stoping is prolonged, the amount of secondary magma formed by abyssal solution must be considerable. Here we reach the most vital phase of the subject, as it is now seen to imply large-scale petrogenesis. However, the matter is, for the moment, chiefly important as it suggests another test of the hypothesis concerning intrusive mechanism.

The average wall-rock is of gneissic or granitic composition. The primary basalt of an abyssal wedge must be acidified by the solution

[1] W. H. Weed, 20th Ann. Rep., U. S. Geol. Survey, Pt. 3, 1900, p. 456.

[2] J. V. Lewis, Ann. Report, State Geologist of New Jersey, for 1907 (1908), p. 132.

of the average xenolith in depth. As we shall note in Chapters XII, XV, XVI, and XX, there are plenty of proofs that much of the new acid magma will rise to the roof, either as such or after the "differentiation" of the xenolith-basalt mixtures. In general, then, great batholiths should, at their upper levels, be of granitic composition. If thick sediments form a large part of the sunken material, the differentiate at the roof will differ more or less conspicuously from granite. A fair judgment of the facts recorded in Chapters XII and XVI to XX must lead to the belief that this test of the stoping hypothesis, when founded on the basal premise of substratum-injection, is fully met. In the next chapter the subject of abyssal assimilation will be more generally discussed.

CHAPTER XI

MAGMATIC ASSIMILATION

Introduction.—Few questions in geology are more important than that as to the capacity of eruptive magmas to dissolve the country rocks. It must evidently concern a petrogenic theory which assumes the basaltic substratum to be the seat of igneous action since the Keewatin lavas were extruded. The question has been and still is answered in exactly opposite ways by able authorities. However, many field studies of the last twenty years have given results suggesting the great importance of magmatic assimilation. Iddings, Brögger, Loewinson-Lessing, Harker, Clarke, Doelter, and others have reviewed the history of opinion on the matter and it is not necessary to repeat the statement.[1] The petrographers who have opposed the idea of magmatic assimilation as a leading factor in rock genesis include Rosenbusch, Brögger, Vogt, Harker, Cross, Iddings, Pirsson, and Washington. Those who have favored the idea include Kjerulf, von Cotta, Fouqué, Michel Lévy, Lacroix, Barrois, E. Suess, Loewinson-Lessing, Hibsch, Johnston-Lavis, E. C. Andrews, Coleman, Sederholm, Barlow, Brock, and N. H. Winchell.

Most geologists, even those specially engaged in the mapping of igneous terranes, have either not considered the problem seriously or have refrained from publishing the product of their thought concerning it. Many geologists have mapped and discussed igneous terranes with clear indication of their opinion that assimilation has no essential place in petrogenesis. The writings of still others show that petrogenic theory is to them a closed book and these authors have been content with color mapping and empirical description. The common failure of field workers to think intensely about their rocks—and that means in terms of origins—is a serious misfortune for geology. Without explanation ever in mind, vital facts are bound to escape observation and record. A signal instance is afforded in a vast number of published papers dealing with eruptive masses. These memoirs,

[1] J. P. Iddings, Bull. Phil. Soc. Washington, Vol. 12, 1892, pp. 91–127; W. C. Brögger, Vidensk. Skrifter, I, Math.-Naturv. Kl. No. 7, Christiania, 1895, p. 116, F. Loewinson-Lessing, Compte Rendu, VII[e] Congrès Géol. Internat., 1899, pp. 308–401; A. Harker, The Natural History of the Igneous Rocks, New York, 1909, p. 83 ff. and 333 ff.; F. W. Clarke, Bull. 491, U. S. Geol. Survey, 1911, p. 294; C. Doelter, Petrogenesis, Braunschweig, 1906, pp. 109–123.

often of great length, give either no account or a meagre account of the country rocks, so that the work of such authors is not directly useful in testing the hypothesis of magmatic assimilation.

Heat Supply and Magmatic Temperatures.—Our inquiry may logically begin with a review of the facts indicating the amount of magmatic energy available for the solution of foreign rock. We need not stop to consider the countless experiments, made either specifically or incidentally in the industries, to prove the solubility of each kind of rock in the other kinds. Even the mattes of the smelter become more or less miscible with their slags if the temperatures are high enough. The prevailing theory of magmatic differentiation itself suggests the high probability that assimilation has often occurred on a large scale. If, with falling temperature, a partial magma becomes immiscible with and separates from its magmatic complement, the two materials, if in contact, should remix with sufficient rise of temperature. Magmatic differentiation is, thus, a reversible process and one cannot but wonder how certain advocates of the universality of that process have been such uncompromising opponents of the assimilation idea. The possibility of the solution of solid rock in a magma is clearly a question of heat supply. If an ordinary magma is at all superheated at a contact, the ordinary country rock must be dissolved, just as ice is dissolved in a large volume of water with a temperature above 0° C.

The heat necessary for assimilation may be developed in several distinct ways; these will be successively considered.

1. The primary heat of the substratum, even if it be fluid, may not now give it a temperature as high as the melting point (about 1100° C.) of holocrystalline basalt at the earth's surface. Under the quiet conditions of the interior, the primary liquid may be supercooled to some extent. That influence of supercooling on the temperature is at least partially, if not more than, offset by pressure control, for pressure raises the fusion-point of basalt. Vogt has estimated that the weight of 25 miles of crust rock raises the fusion-point about 50° C., but he is careful to state the uncertain nature of the experimental data on which his calculation is based.[1] The actual effect of pressure may be still greater.

2. If the viscosity of the undisturbed substratum material is kept high because of undercooling as well as pressure, it follows that considerable heat must be developed in the very act of injection into the crust. How important this cause may be cannot be stated but corresponding elevation of temperature in the abyssal wedge may con-

[1] J. H. L. Vogt, Videnskabs-Selskabets Skrifter, I, Math.-naturv. Kl., 1904, No. 1, Christiania, p. 210.

ceivably be more than 100° C. This additional energy is, of course, due to the conversion of the work done in the massive readjustments of crust and substratum outside the magmatic wedge. On the other hand, the expansion of the liquid magma in rising to levels of lessened pressure must have a cooling effect, of uncertain magnitude.

3. Some superheat might be expected in a great abyssal wedge of magma, part of which has been drawn from a level well below the bottom of the solid crust. It is probable that the substratum is itself chemically stratified. Thermal-convection currents are, thus, impossible or else are too weak to affect essentially the normal temperature gradient, which may continue nearly unchanged from its value in the overlying crust downward into the basaltic shell. The tapping of the lower layers of the substratum during the injection of a very great abyssal wedge might thus introduce some magma distinctly hotter than that just below the crust.

4. Surface blanketing may produce some superheat in the eruptible part of the substratum just beneath. Such blanketing is exemplified in geosynclinal sedimentation, in the formation of the greater volcanic piles, and in the local thickening of crust rock by close folding and overthrusting in mountain systems. The inevitable rise of the isogeotherms beneath such blankets must tend not only to fuse the lower part of the crust but also to raise the temperature of the basaltic layer, which is then subject to injection.

5. If radioactive matter is really concentrated in the outermost skin of the earth, a superficial rock blanket must cause a heating, not only of the crust but of the substratum as well.[1]

6. In any case blanketing will heat the crust rocks beneath the blanket and so far facilitate their solution in abyssally injected magma.

7. An even more important heating of the country rock is the biproduct of orogenic crushing and of dynamic metamorphism. Any such independent raising of temperature in the wall rocks of an abyssal wedge obviously tends to postpone the freezing of the wedge and thus to lengthen its life as an active solvent.

It is impossible to say how great may be the combined effects of the several factors affecting magmatic temperature, but it would be rash to assume maximum superheating of the primary basalt to an amount greater than a few hundred degrees. We shall, for the purposes of further discussion, assume a maximum average temperature of 1300° C. in the larger magmatic wedges.

Observed Temperatures at Volcanic Vents.—The lava lakes of the world cannot be expected to indicate the maximum or average superheat developed in an abyssal wedge. No accurately measured

[1] Cf. J. Joly, Radioactivity and Geology, London, 1909, p. 108.

volcanic temperature exceeds 1200° C. As described in Chapter XIII, such vents are kept open by the fluxing of crust-rock which, by rapid radiation into space, tends to assume temperatures only a few degrees above the zero point.

Nevertheless, some degree of superheat is manifest even in extrusive bodies. The very fact that the life of volcanic vents is often to be measured in milleniums strongly suggests that their feeding magmatic wedges were considerably superheated at the time of injection. It is difficult to believe that, at times of great activity, the lavas of Kilauea are not considerably hotter than is shown by the 1911 temperature (1010° C.) of the "Old Faithful" center in that lava lake, as measured by Shepherd and Perret. The incandescence of the lava in the "caves" at the edge of this lake in 1909 was certainly higher than that of the lava in the "Old Faithful fountains." Similarly, the testimony of several good observers, that the lava in the vastly greater fountains in Mokuaweoweo (Mauna Loa) has often been "white hot" or "dazzling white," is not to be lightly set aside. The actual surface temperatures reached at this greatest of active volcanoes may be as much as 1300° C.

Observed Liquefaction of Country Rocks.—A further indication of superheat in basaltic magma is given in the facts recorded by Lacroix and von John.[1] These authors describe instances where blocks of gneiss, reaching the size of a cubic meter, have been "entirely transformed" into porous glass by immersion in basalt on its way to the earth's surface. Ordinary gneiss is not a specially hydrous rock and its temperature of liquefaction is doubtless more than 100° C. higher than the temperature of consolidation of basalt. The difference may well be more than 200° C.; and it would still be a minimum value for the possible degree of superheat for the primary magma.

In some cases visible xenoliths have been softened and partly dissolved by acid, batholithic magma. The fact that such a block has not sunk to depths far below the reach of erosion implies very high viscosity for the magma at the moment of enclosure. That viscosity means a relatively low temperature, probably no higher than the inversion-point of quartz, namely, 870° C. *Some* assimilation is, therefore, possible even in the greatly supercooled acid magma. How much more rapidly must it occur in magmatic wedges even no hotter than the visible lavas of Sicily or Hawaii!

Fluxing by Concentrated Volatile Matter.—So far we have considered the possibility of solution only through superheated, homogeneous magma, especially the primary basalt. Yet to subterranean

[1] A. Lacroix, Les Enclaves des Roches Volcaniques, Macon, 1893, p. 563–5; C. von John, Jahrb. d. k. k. Reichsanstalt, Vienna, Vol. 52, 1902, p. 141.

solution there are powerful aids other than the mere superheating of the magmatic wedge.

First, the influence of gas concentration may be noted. It is well established that some gases under pressure will form fluid solutions with rock matter at temperatures far below the fusion point of ordinary minerals and rocks. The well known experiment of Barus represents an extreme case. He found that water and silica in a sealed tube form a liquid at 210° C.[1] Fouqué and Michel Lévy proved that the materials of a very acid granite (79 per cent. of silica) mixed with water in a sealed tube, became at least partly fluid at 1000° C.; though the dry materials did not become "even viscous" at 1300° C.[2] Other gases must have corresponding effect on silicate melts.

Without further illustrating this universally accepted principle of fluxing by volatile matter, we may conclude that a concentration of either primary gases or gases derived from adjacent sediments greatly facilitate magmatic solution. As stated in Chapter XIII, the mere change of pressure involved in abyssal injection doubtless causes the special concentration of the primary volatile matter at the top of the magmatic wedge. The secondary gases, introduced from invaded sediments or other wall-rocks, will similarly tend to assemble at the top of the magmatic chamber. In each case the concentration takes place in the part where the gas is most efficient in helping to dissolve the maximum amount of country rock in the magma.

To the French school of geologists belongs the distinction of having long emphasized the influence of magmatic gases in the production of secondary magmas. Those observers have not assumed the existence of a basaltic substratum as a necessary prerequisite to igneous action in Keewatin and later times; yet their arguments in favor of gaseous influence in assimilation are also, for the most part, good under that assumption.

Influence of the Mixture of Rock Matter on Liquidity.—Again, mere chemical contrast between two rocks tends to lower the temperature of their mutual solution. The principle is exactly the same as that just mentioned in the case of the gaseous fluxes, and there is general agreement among physical chemists as to its truth in the present instance. A single example will illustrate the efficiency of this kind of fluxing. Petrasch has experimentally shown that two parts of limburgite and one part of Predazzo granite will melt together at 950° C., and that the solution remains fluid down to 850° C.[3] Predazzo

[1] C. Barus, Amer. Jour. of Science, Vol. 9, 1900, p. 161.

[2] F. Fouqué and A. Michel Lévy, Comptes Rendus, Vol. 113, 1891, p. 283. Also personal communication from Mons. Michel Lévy.

[3] K. Petrasch, Neues Jahrb. für Mineralogie, etc., B. B. 17, 1903, p. 508.

granite softens at 1150° C. and the limburgite at 995° C.[1] The freezing point of the mixture was, therefore, 300° C. below the melting point of the granite and 145° C. below that of limburgite.

Magmatic Stoping in Relation to the Low Temperatures of Consolidation for Batholithic Rocks.—Assuming the validity of the "geological thermometer" now being constructed by the Geophysical Laboratory of the Carnegie Institution of Washington, each of the ordinary granites has been at least partly molten at a temperature no higher than 870° C. nor lower than 575° C.[2] Both undercooling and the presence of volatile matter in the batholithic magma are doubtless responsible for this low temperature of final consolidation. At that temperature, solution of the country rocks along the main contacts may be almost infinitely slow, but magmatic stoping may still continue and therewith we have the possibility, if not the necessity, of assimilation in great depth. (See page 216.)

It seems likely, then, that assimilation would continue in a magmatic wedge of batholithic proportions until its average temperature fell to 900° C. and perhaps lower.

Available Heat for Assimilation in Batholithic Masses.—Since, for the substratum-injection hypothesis, the heat problem is most serious as regards the greatest of the intrusive bodies, it will be well to illustrate the inferred possibilities of assimilation by a quantitative discussion of granite batholiths. The substratum-injection hypothesis involves a secondary origin for all post-Keewatin granites. The writer has, on several occasions, explained most of these as differentiates from solutions of the earth's acid shell in basaltic wedges injected from the substratum; and that view is already implied in the earlier theoretical part of the present book. The average country rock of the upper half of each batholith is either acid gneiss or a type chemically identical with it.

The assumed range of temperatures characterizing the active magmatic period of a major injection is from 1300° C. to 900° C. The energy emitted by 1 gram of liquid basalt cooling from 1300° C. to 900° C. is about $(400 \times .33) = 132$ calories. The total melting-heat of gneiss, if molten at 900° C., is about 350 calories. If we neglect heat of solution (positive or negative), 10 grams of the primary basalt would render molten about $10 \times \frac{132}{350} = 3.8$ grams of gneiss, if all the surplus heat of the basalt were available for the solution of the gneiss. So far as the assimilation is further aided by magmatic gases, the proportion of gneiss capable of solution in a unit mass of the basalt would be still higher.

[1] C. Doelter, Tscherm. Min. u. Petrog. Mitt., Vol. 20, 1901, p. 210.

[2] F. E. Wright and E. S. Larsen, Amer. Jour. Science, Vol. 27, 1909, p. 421.

We seem, therefore, not to stretch the probabilities of the case, nor to contravene known facts, when we conclude that a limited but important amount of assimilation in primary basalt is theoretically possible.

The actual calculation suggests that the magnitude of permissible assimilation may be of the order demanded if, for example, a Tertiary granite is due to the assimilation of silicic rocks in a primary basaltic wedge. If the wedge of liquid basalt stood originally to a height of 20 miles above the substratum level, its heat content might suffice to melt up a mass of gneiss of the same average horizontal extent and from 6 to 8 miles deep. In fact, such may be the order of depth for the granite of post-Cambrian batholiths. Unfortunately, erosion has seldom or never penetrated as much as 4 miles into such a batholith, so that this rough deduction cannot be directly checked by observation.

However, the justice of the assimilation theory becomes only fully apparent when the chemistry and field relations of the different igneous-rock types have been reviewed in some detail. Such a review, though a partial one, is made in Chapters XV to XX.

We may now continue the general outline of the subject by noting the characteristics of magmatic solution in its two leading phases.

Marginal Assimilation.—No informed worker on the igneous-rock problem needs to be reminded of the rarity of the cases where the contact of magma and country rock is marked by shells of transition material. Generally there is no chemical "consanguinity" directly evident between intrusive and wall rock. A granite batholith often contacts with gneiss, greenstone, quartzite, argillite, or limestone, and yet the contact phase of the intrusion is everywhere of essentially the same composition. Only very rarely have large rock bodies, like those of the Haute Ariège (Pyrenees) or the contact phase of the Alnö stock (Fig. 184), been explained as due to direct melting-together (syntexis).[1] The exceptions surely prove the rule in this case.

Such failure of transition rocks or of direct evidence of consanguinity have prompted many petrologists, including those listed in an early paragraph of this chapter, to deny forthwith the efficiency of assimilation in forming large bodies of magma.

Yet we have already seen that this suggested test of the hypothesis cannot be conclusive. In the nature of the case notable assimilation is to be expected only in very great bodies of magma, that is, generally only in batholiths. Apart altogether from theory, it is plain that *some* stoping has occurred in practically every subjacent body. There-

[1] A. Lacroix, Bull. des serv. carte géol. de la France, Nos. 64 and 71, 1898, 1900; A. G. Högbom, Geol. Fören. Förhand., Vol. 17, 1895, p. 132.

fore their main contacts, at least in part, were established after the magma had been *somewhat* cooled. The suspension of xenoliths in their visible positions proves beyond peradventure that the enclosing magmas were nearly frozen when the blocks were broken off from wall or roof. In such a case the block could not be digested unless there were a local concentration of fluxing material, such as a considerable percentage of water in the block itself. A much more important consideration is that the stoping of the earlier period, when the magma was an energetic solvent, removed from roof or wall the syntectic films and shells as fast as these were formed. Roof, wall, and xenolith are generally free from syntectic shells because the period of stoping must be longer than the period of solution. Perhaps the stoping hypothesis has its greatest psychological value in henceforth forbidding the use of this time-worn argument against assimilation. Moreover, the opponents of this doctrine have failed to allow for the highly probable fact that magmatic differentiation can occur at temperatures below those of active assimilation.

For several reasons, therefore, chemical evidences for or against marginal assimilation must generally be *indirect*.

Abyssal Assimilation.—However, we have observed the improbability that marginal assimilation alone is competent to explain the observed amount of replacement performed by batholithic magmas. Nor can it explain the huge volumes of secondary magma which, on the substratum-injection theory, have been formed by injected wedges of primary basalt. Our way is clear if we follow the stoping hypothesis to its inevitable corollary, *abyssal* assimilation. In most cases nearly all of the sunken blocks *must* be melted or dissolved or both.

Illustrations of pure-melting of blocks enclosed in extrusive basalt are recorded by Lacroix, von John, and others, as above noted. These and many other writers have described numerous cases of mutual solution in lavas as well as in intrusive magmas which could not remain liquid for a tenth of one per cent. of the time allowable for a typical subjacent body. It is little wonder that Brögger, though one of the leading opponents of the marginal assimilation theory, is willing to credit magma in depth with great assimilative power.[1] His statement implies that he had chiefly in mind marginal assimilation. The present writer heartily agrees with that conclusion. Abyssal assimilation must occur on the main contacts of abyssal wedges at great depth, and it may be responsible for a notable part of the secondary magma in a batholith. But the other type of abyssal

[1] W. C. Brögger, Die Eruptivgesteine des Kristianiagebietes, Vol. 3, 1898, p. 350.

assimilation, namely, that represented in the solution of sunken xenoliths, has certain advantages over pure marginal solution, which we shall do well to review.

First, marginal assimilation is largely effective only in the earliest parts of the magma's history, when it is absolutely and relatively very hot. There is thus an early time-limit fixed for the gigantic work of dissolving the thousands of cubic kilometers actually replaced in the intrusion of a large batholith.

Secondly, on the older view the assimilation takes place primarily on main contacts and along a relatively limited amount of surface. For example, a cube of wall-rock 1 kilometer in diameter can offer only about 6,000,000 square meters of surface at a time to the dissolving magma. If that same cube were shattered into cubes 10 meters on the side and then engulfed, the magma would carry on the work of solution on 600,000,000 square meters of surface. If the shatter-blocks were cubes one meter in diameter the original surface would have been increased one thousand times.

Thirdly, the average crust rock, being allied to gneiss, dissolves at a lower temperature in basic magma than in acid. On the stoping hypothesis, solution of the xenolith generally occurs in the lower, basic part of the magmatic chamber; on the older view, it is the granitic magma which must do most of the work of solution. For even if the originally injected magma is a basalt, the products of its assimilating activity, which are more acid and less dense than itself, must remain at the batholithic roof and rapidly assume the chemical composition of mean mountain rock. It follows that the primary magma must be very much more superheated than is required on the stoping hypothesis or than seems easy of explanation, in view of the difficulty of understanding how plutonic magma, which is capable of intrusion, can become superheated more than 200° or 300° C.

Fourthly, the stoping hypothesis has the special advantage of providing a mechanism of thorough agitation within a batholith. Strong stirring of the mass is induced by the sinking of xenoliths and by the necessary rising of the magma locally acidified by their solution. This agitation can explain the marvellous homogeneity in each large batholith. It helps greatly to explain the manifest evidences of magmatic differentiation within batholiths—splittings and segregations that cannot be due to the slow process of molecular diffusion or to mere thermal convection. The whole process of stoping and the rising of syntectic magma tends to equalize the temperatures in the batholithic chamber and thereby we can understand the even grain and rapid, nearly simultaneous crystallization of a batholith throughout its visible depth.

Fifthly, the engulfment of blocks of geosynclinal sediments enriches all parts of the batholiths with water, chlorides, etc., which so greatly aid in solution; while, on the older view, these agents are confined to the uppermost part of the chamber.

Sixthly, as already noted, the cleansing of syntectic films from contact of solid and liquid is much the more rapid and perfect according to the stoping hypothesis, thus providing and renewing conditions for molecular lowering of the fusion-point along contacts.

In short, the newer view has not only the advantage of better explaining the facts of the field but it is incomparably more economical of the heat postulated for the work of batholithic replacement than is the theory of pure marginal assimilation. Melting and marginal assimilation of country rock takes place in the initial, superheated condition of a basaltic injection, but must be regarded as always subordinate in replacement efficiency to stoping and the corresponding type of abyssal assimilation.

Assimilation in Intrusive Sheets.—Probable as large-scale solution in depth may be, the argument for assimilation has been greatly strengthened by recent discoveries in the geology of injected bodies. These igneous masses have floors, which can often be located in actual outcrop. If both roof and floor as well as the body itself are well represented in outcrop, we have an approximation to the petrogenist's ideal. He can never rest assured of his conclusions regarding the chief chemical processes in abyssal wedges or batholiths until he has compared the chemical dynamics plainly exhibited in the smaller intrusions. Since injected bodies are generally narrow and therefore rapidly chilled, the conditions for their extensive assimilation of country rock are bound to be rarely represented. Of the total number of injections sufficiently large, only a few have both roof and floor preserved. This is clearly one of the reasons why the doctrine of assimilation has not hitherto won the general recognition it deserved. It has already attained new dignity in the minds of several petrologists by offering the only feasible explanation of the chemical facts recorded in the few properly exposed, large bodies of igneous rock. One may doubt that any other line of study will shed light so rapidly on the ultimate problems of petrogenesis. Speculations regarding the origin of the vast, "bottomless" intrusives are to be both suggested and controlled by direct observations on the larger underground "slag-pots" which can be examined from top to bottom.

The thicker sills and interformational sheets are obviously those injected bodies which are of most significance. They are offshoots from main abyssal injections and they have a characteristic form which shows their initial temperatures to have been relatively high.

The wide extension of intrusive sheets cannot be explained unless their magmas possessed some initial superheat, notwithstanding the partial cooling in the dike fissures or other feeding channels. In other words, the initial temperatures of intrusive sheets approach, though probably never reach, the maximum temperatures of the parent magmatic wedges. If, then, it can be shown that notable assimilation has occurred in the sheets, we are forced to credit the possibility of assimilation on a much larger scale in the abyssal wedges.

The writer has collected the pertinent facts regarding some of the thicker sheets already mapped and described.[1] These and additional facts are summarized in Chapters XII, and XV to XX. The many details need not be repeated here. The more salic magma in each one of these sheets is simply explained by the principle of assimilation and seems to fail of explanation if that principle be excluded. The chief motive in reaching the conclusion is the chemical "consanguinity" between each salic magma and its country rocks.

The assimilation in an intrusive sheet may take place at roof and floor, or within the mass, by the solution of blocks stoped down from the roof or, much more rarely, stoped *up* from the floor. As far as secondary magma is thus formed, it is relatively easy to discern the "consanguinity" mentioned in the last paragraph. But the proofs of it may be obscured, in many cases, by several complications incidental to intrusion of the sill type.

Generally the channels (dike fissures) through which magma is forced on its way to the sill chamber, are relatively few and are very narrow when compared with the thickness of the sill. The magma must flow through the channels during a considerable time in order to fill the great chamber. At that stage the magma is at its hottest and is being moved rapidly past the wall rocks of the channels. The solution of those rocks, in depth, must be stimulated by the movement as well as compelled by the high temperature. Arriving in the chamber, the magma is already secondary in part and that portion may differ chemically from the roof and wall rocks of the sill itself.

Again, the character and field relations of the Moyie sills (see page 344) suggest that a magma, after forming a thick sill in a sedimentary series, sometimes breaks through the roof and forms a sill at a higher horizon. The secondary magma developed in the first chamber may contrast essentially with that which could be due to the assimilation of the country rocks at the higher level.

In spite of the causes for uncertainty in individual cases, the evidences that the assimilation hypothesis meets this "consanguinity"

[1] R. A. Daly, Amer. Jour. Science, Vol. 20, 1905, pp. 185–216; and Festschrift zum siebzigsten Geburtstage von Harry Rosenbusch, Stuttgart, 1906, pp. 203–233.

test are very strong. It is safe to say that those evidences cannot be set aside by the petrologists who believe the differentiation of pure primary magmas to be the only important cause of the diversity in igneous rocks.

CHAPTER XII

MAGMATIC DIFFERENTIATION

Introduction.—The kernel of the theory so far presented is the conclusion that late pre-Cambrian and younger magmas have originated either in primary basalt or in syntectics of the substratum basalt and solid rocks. At many points we have noted that this cannot be the whole explanation of the known variety in magmas and in igneous rocks. The inquiry as to the nature of the additional causes is clearly the next step in working out a complete theory. All these supplementary processes, so far as determined, have long been grouped under the general caption, "magmatic differentiation." By this term is meant the separation or segregation of fractional amounts of a magma so that at least one sub-magma, chemically contrasted with the parent magma, is produced. Some authors distinguish "magmatic" differentiation from "Krystallizationsdifferentiation" or modification of a magma by the separation of the solid crystals formed early in the crystallization of that magma. This distinction is not strictly logical, since in the latter case the mother liquor is a true, segregated magma. Nor is it now possible to be sure that, in many cases, the segregation of "crystals" has not taken place when these were still in the liquid phase. A more valid, or at any rate, more useful distinction is that between differentiation through *liquation* and differentiation through *fractional crystallization*. In the first case the segregation of two or more *liquid* fractions is the controlling factor. In the second case the segregation of one or more crops of solid crystals leaves a mother liquor of a new chemical type.

The history of opinion on this complex theme has been written by Teall, Iddings, Zirkel, Schweig, Loewinson-Lessing, Harker, Clarke, and others. Much of the published literature on differentiation really concerns mineralogy and physical chemistry rather than geology. Yet many biproducts of these studies have geological bearing and an exhaustive survey of their geological applications would, alone, occupy a work larger than the present volume.

In this chapter the writer will attempt little more than a statement of opinion as to the relative geological importance of the various modes of differentiation, and therewith a brief indication of the grounds for special faith in those processes. For further discussion the reader is specially referred to Loewinson-Lessing's "Studien über die Eruptivgesteine," which still remains one of the fullest and most suggestive of all the general memoirs on differentiation.[1]

For clearness it is well to distinguish two stages in differentiation: first, the preparation of units; and, secondly, the segregation of those units.

The *unit of differentiation* is either a molecule, a solid crystal, or a small non-consolute fluid portion of the magma. The formation of any one of these is largely a chemical matter and to get to the bottom of it in a given case, the principles of "affinity," vapor pressure, surface tension, and saturation must be applied, and the influence of time, viscosity, superfusion, etc., must be evaluated. These important but endlessly complex problems have already undergone attack; in the writings of Vogt, Iddings, Harker, Elsden, Loewinson-Lessing, and others, the reader will find discussion as to the degree of contemporary success in solving them. For present purposes the mechanism of molecular development, of crystal growth, and of the development of immiscible portions, need not be discussed in detail. The existence of such units will be assumed. Their segregation into large masses is more directly a geological process and will be illustrated in greater detail.

Molecular Diffusion.—Some petrologists have tried to rest in the belief that differentiation could be explained by the segregation of individual molecules. A few authors have even suggested that silicate sub-magmas have been derived by the collection of free oxides within a principal magma characterized by molecular dissociation. However, the destructive criticism of G. F. Becker has showed the almost infinite improbability that such diffusive processes have been directly responsible for the formation of large masses of igneous rocks.[2]

Fractional Crystallization.—That crystals of early formation in a magma are units of differentiation is obvious. Their segregation has been imagined to take place in two different ways—by gravitative sinking and through convection currents. From the day when Charles Darwin published his classic "Geological Observations" to the present time, the hypothesis of magmatic differentiation through the settling of solid crystals has not wanted adherents. Schweig has

[1] F. Loewinson-Lessing, Compte Rendu, 7e Session, Congrès Géologique Internationale, St. Petersburg, 1899, pp. 308–401. See the works listed in the footnote to the second paragraph of Chapter XI. See also J. V. Elsden, Principles of Chemical Geology, London, 1910; J. J. H. Teall, British Petrography, London, 1888; F. Zirkel, Lehrbuch der Petrographie, Leipzig, 1893, Vol. 1, pp. 711–796; M. Schweig, Neues Jahrbuch für Mineralogie, etc., B. B. 17, 1903, p. 516.

[2] G. F. Becker, Amer. Jour. Science, Vol. 3, 1897, p. 21.

probably made the most general application of the principle.[1] At a volcanic vent, magma may be held for many years at temperatures above freezing but below the temperatures where minerals like the olivines, pyroxenes, amphiboles, etc., must crystallize. Under such conditions it would seem necessary that differentiation through this type of fractional crystallization should take place. The writer has thus explained the derivation of pyroxene andesite from basaltic magma, though even here a parallel liquation may dominate.[2]

Becker and Pirsson consider that thermal-convection currents have been efficient in segregating the crystals of early generation.[3] The suggestion has been applied to very few cases where it can be tested quantitatively. In fact, the only instance of the kind seems to be that of the Shonkin Sag laccolith in the Highwood Mountains, Montana. Pirsson has stated the argument in the following form:

"At some period crystallization would take place, and this most naturally would begin at the outer walls. It would not begin at the top because the material would arrive there from below at its highest temperature. Moving off toward the sides the material begins to cool and descend and becomes coolest as it nears the floor; there crystallization would commence. The first substance to crystallize is the solvent, which in this case would be the femic minerals, chiefly augite. Part of the material solidified would remain attached to the outer wall and form a gradually increasing crust, and part would be in the form of free crystals swimming in the liquid and carried on in the current. Probably at first, as the liquid moved inward over the floor of the laccolith and became reheated, these crystals would remelt, giving rise to numerous small spots of magma of a different composition, which would slowly diffuse. As time went on, however, there would be a constantly increasing tendency for the crystals to endure; they would be carried greater and greater distances. But as they are solid objects and of greater specific gravity than the liquid, there might be a tendency for the crystals to drag behind and accumulate on the floor of the chamber. Moreover, from the heat set free at the time of their crystallization and from the resulting concentration of the chemically combined water vapor in the magma, the residual liquid would tend to have its mobility kept undiminished, since these would be factors which would tend to counteract the increase in viscosity due to cooling. In this manner it may be possible to understand how there would form a femic marginal crust and a great thickness of the femic material at the bottom of the laccolith. As the cooling went on the edges of the outer crust would rise more and more toward the top, finally spreading over it, and as a result the crust would be thinner on the top than elsewhere, as in the Shonkin Sag laccolith, in which the upper crust of femic rock is still preserved."[4]

[1] M. Schweig, Neues Jahrbuch für Mineralogie, etc., B. B. 17, 1903, p. 563.

[2] See page 375, and R. A. Daly, Jour. Geology, Vol. 16, 1908, pp. 401–420.

[3] G. F. Becker, Amer. Jour. Science, Vol. 4, 1897, p. 257; L. V. Pirsson, Bull. 237, U. S. Geol. Survey, 1905, p. 187.

[4] L. V. Pirsson, Bull. 237, U. S. Geol. Survey, 1905, p. 188.

But one may well question that thermal convection could be so efficient in distributing the products of fractional crystallization in this laccolith. Before the intrusion the strata now forming its roof and floor had practically the same temperature. There is nothing to indicate that the floor was of a higher temperature than the roof during the magmatic period. The laccolith is only 140 feet thick, so that it must have been frozen before the theoretically more rapid cooling at the roof could establish any practical difference of temperature between roof and floor rocks. Again, even if that difference were 100° C., the convection gradient would be less than one-eighth as steep as that in an equal thickness of water similarly heated. Our idea of the speed of convection in an ordinary beaker of ice-cold water placed over a flame must be drastically modified in appreciating the case of a column of water 140 feet high. Moreover, the speed of convection is a direct function of viscosity. The viscosity of the Shonkin Sag laccolith, being under pressure, could hardly have been less than fifty times that of water at atmosphere pressure, and the ratio more probably ran into the hundreds of thousands. It is no exaggeration to say that the speed of currents due to pure thermal convection in this laccolith must have than been millions of times less than that in a hot-air furnace, and many thousands of times less than the speed of convection in an ordinary beaker in the laboratory. In this matter, as so often in geological dynamics, we must think to scale.

Finally, the time available for convective distribution in the Shonkin Sag laccolith was very limited. In a body so thin, even if initially superheated as much as 500° C., conduction into the cool rocks above and below would certainly chill the mass to the point of prohibitive viscosity within the period of one year. If, as is more probable, the initial superheat was no more than 100° C., thermal convection would doubtless be unable to affect the composition of the 10-foot contact phase of the laccolith after the lapse of one week.

We conclude that, from the slowness of convection and the shortness of the magmatic life of this laccolith, the basic contact shell of the Shonkin Sag laccolith cannot be explained by the combined influence of thermal convection and fractional crystallization. The same general argument and the same conclusion apply also to the Square Butte laccolith, for which Pirsson has evolved a similar explanation. Even for large laccoliths one may well question the efficiency of this thermal-convection hypothesis on the quantitative side. It is also weak on the chemical side. In no described case is the basic contact-phase at roof or wall of an intrusive body of the composition expected on this hypothesis.

Liquation.—Ostwald points out that the number of liquids miscible only within definite limits is much greater than is the number of those which mix in all proportions.[1] Since magmas are solutions, it is *a priori* wise to consider their possible differentiation through the principle of limited miscibility at certain temperatures. Though Vogt has held that this principle does not, in general, apply to silicate mixtures, one of his latest publications contains the statement that magmatic differentiation consists in the splitting of liquid phases, which splitting is controlled by the laws of eutectics.[2] Unless the writer misapprehends his meaning, therefore, Vogt has come to recognize limited miscibility as a general law for silicate solutions as soon as these approach the consolidation interval of temperature.

Richards and Ostwald believe that solid crystals develop from a transitory liquid phase in the case of substances which melt at temperatures not far from their respective temperatures of crystallization—a condition realized in the case of most rock-forming minerals.[3] From specially designed experiments Slatowratsky and Tammann have concluded that, for naphthaline, yellow phosphorus, $CaCl+H_2O$, potassium, sodium, or ice, the passage from the solid phase to the liquid is marked by "plastic crystals,"[4] Dittler adopts this view also for the silicate, anorthite.[5] Schade's microscopic studies showed that the formation of crystals of cholesterol from an alcoholic solution is preceded by a separation of the substance in the form of liquid drops. He observed similar indications for solutions in ethyl ether and in oils, as well as when the pure molten substance was rapidly cooled. The freshly formed, acicular crystals were very plastic, but this plasticity diminishes with time.[6] Von Weimarn holds that the liquid-crystalline state is a general property of matter at the appropriate temperature.[7] Quite recently Buchanan has described a remarkable series of observations on saturated solutions. He used a saturated solution of calcium chloride and water as a type. It was kept at a constant temperature and at intervals the density was very carefully determined. The result was to prove a dilatation of the solution for a considerable time preceding the appearance of the first solid crystal of calcium chloride. This change of volume is of the same quality

[1] W. Ostwald, Solutions, 1891, p. 39.

[2] J. H. L. Vogt, Videnskabs-Selskabets Skrifter, I, Math.-Naturv. Klasse, No. 10, Christiania, 1908, pp. 6 and 102.

[3] T. W. Richards, Phil. Mag., 1901, p. 500.

[4] N. Slatowratsky and G. Tammann, Zeit. f. phys. Chemie, Vol. 53, 1905, p. 341.

[5] E. Dittler, Tscher. Min. u. Petrog. Mitt., Vol. 29, 1910, p. 273.

[6] H. Schade, Koll. Chem. Beihefte, Vol. 1, 1910, p. 391.

[7] P. P. von Weimarn, Zeit. Chem. Ind. Kolloide, Vol. 3, 1908, p. 166.

as that produced in the system by actual crystallization. Buchanan concludes that the "stretching" of the solution, before a solid phase is formed, reflects a "new creation" in that solution. One may infer that he means a partial concentration of the calcium chloride about centers.[1]

These analogies suggest that the solidification of a very slowly cooled intrusive magma may be preceded by a long period in which one or more chemical components form small liquid globules or crystals.

More generally, we must also allow for the possibility that a homogeneous magmatic solution may become broken up into non-consolute portions in a certain region of temperature and pressure. Immediately after the formation of these fractions, the magma would be an emulsion. The often-repeated statement that the dominant rock-forming materials are miscible in all proportions has seldom been properly guarded. It may be quite true for high temperatures and yet quite untrue for a temperature just above that of crystallization of a given component. No one has yet succeeded in holding a molten mixture of silicates within this narrow range of temperature for a length of time sufficient to warrant any definite conclusion on the matter.

On the other hand, there are some facts suggesting that limited miscibility has actually characterized natural magmas just before their final freezing. Most basic segregations and probably all orbicular granites, diorites, and gabbros are direct evidences of the emulsion stage. The common banding of nephelite syenite, the banding of certain gabbros, the phenomena of some differentiated dikes (Entmischte Gänge) are other illustrations of true magmatic splitting. The constitution of the Moyie sills or of the Sudbury sheet (see Chapter XVI) is inexplicable except on the assumption of the limited miscibility of granitic (micropegmatitic) and basaltic (gabbroid, noritic) magma under certain conditions. In this connection Bäckström's point that there is a lack of intermediate rocks in the liparite-basalt field of Iceland has great significance.[2] The sulphidic ore of Sudbury became non-consolute with the norite just as matte is non-consolute with its slag. Partial immiscibility is illustrated even in the brief period of liquidity allowed to artificial glass in the factory.

Harker's objection to this application of the principle of immiscibility at certain temperatures is that it involves discontinuous variation between different parts of a single rock-body instead of the actually observed continuous variation. But, in the first place, the

[1] J. Y. Buchanan, Trans. Roy. Soc. Edinburgh, Vol. 49, Part I, 1912, p. 194.

[2] H. Bäckström, Jour. Geology, Vol. 1, 1893, p. 773.

separation between such silicate differentiates *is* in many cases remarkably sharp, especially when we consider the scale of operations in magmatic chambers. Secondly, we could hardly expect the separation to be as perfect between these viscous and highly complex magmatic fractions as, for example, the separation between phenol and water.

In summary, it may be stated that a host of field and laboratory observations favor the application of the liquation (limited miscibility) principle to natural silicate magmas; and that not a single fact is known to the writer which conflicts with that assumption. The efforts of physical chemists should be spent, not on denying its validity, but in defining the conditions under which the liquation so often demonstrable in nature has taken place.

Loewinson-Lessing's suggestion, that the equilibrium of a homogeneous magma, at nearly constant temperature, may be disturbed by the solution of a small quantity of the country rock, is worthy of close attention.[1] Linebarger, Duclaux, and others have shown that a solution of each of many colloids can be made to coagulate or gelatinize by the addition of a mere trace of a certain substance.[2] This analogy aids the imagination in following the process described by Loewinson-Lessing, which so far lacks full experimental proof.

Gravitative Differentiation.—The sinking of crystals is expected to have its maximum differentiating effect within volcanic vents where the agitation of the magma tends to prevent undercooling and to promote crystallization, while the magma retains relatively low viscosity. These conditions are chiefly due to the upward passage of gases in volcanic vents, which in this respect are contrasted with dikes, sheets, and laccoliths. The steady or intermittent passage of hot gases through the lava columns at surface vents is competent to keep the column long within the temperature interval of crystallization. (See page 288.) Nevertheless, liquation may co-operate even in this case. In general, it is probably a much more efficient cause of differentiation than fractional crystallization but the relative importance of the two processes can be estimated only after the physical chemistry of magmas becomes better understood. Meanwhile we may use the expression "*gravitative differentiation*" as a name for the chief mode of magmatic separation, without implying that fractional crystallization or liquation is the more active in a given case. However, experiments like a well known one by Morozewicz favor the liquation hypothesis.[3] (See p. 363.)

[1] F. Loewinson-Lessing, Compte Rendu, 7e session, Cong. Géol. Internat., St. Petersburg, 1899, p. 377.

[2] C. E. Linebarger, Jour. Amer. Chem. Soc., Vol. 20, 1898, p. 375; J. Duclaux, Comptes Rendus, Vol. 138, 1904, p. 144.

[3] J. Morozewicz, Tschermak's Min. und Petrog. Mitt., Vol. 18, 1898, p. 232.

Differentiation at Central Vents.—The control of gravity is suggested in the volcanoes of Réunion, Hawaii, and the Juan Fernandez Islands. During the 1874 eruption in Réunion, lava flows issued simultaneously from the summit of the active cone and from a lateral fissure which doubtless communicated with the main vent in depth. The summit flow was an augite andesite with 57.49 per cent. of silica and a specific gravity of 2.79. The lava from the flanking fissure was a basalt rich in olivine, with a silica percentage of 48.98 and a specific gravity of 2.97.[1] The base of Mauna Kea, Hawaii, is chiefly a pile of flows of olivine basalt. On ascending the cone that type is succeeded, in order, by olivine-poor basalt, augite andesite, and, at the summit,

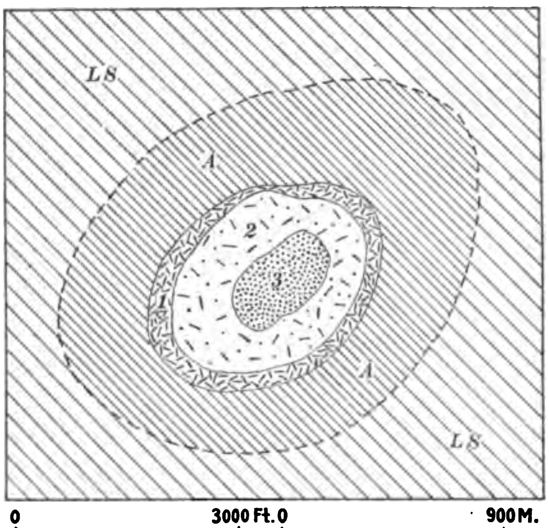


Fig. 120.—Plan of Mt. Johnson, Quebec. (After F. D. Adams, Jour. Geol., Vol. 11, 1903, p. 255). *LS*, Lower Silurian sediments; *1*, pulaskite; *2*, intermediate rock; *3*, essexite; *A*, contact aureole in *LS*.

trachydoleritic lava with a silica percentage of about 51 and a specific gravity (holocrystalline phase) of 2.76.[2] Similarly, Quensel has found that the lower-lying lavas of Masafuera, one of the Juan Fernandez Islands, are basic olivine and plagioclase basalts, succeeded above by basanitic lava, which in turn is overlain by soda-trachyte with a silica percentage of 63.43.[3]

Adams regards Mt. Johnson, Quebec, as a volcanic neck. The concentric development of pulaskite, transition rock, and essexite is

[1] C. Vélain, Mission de l'île Saint-Paul, Paris, 1888, p. 181.
[2] R. A. Daly, Jour. of Geology, Vol. 19, 1911, p. 297.
[3] P. D. Quensel, Bull. Geol. Inst. Upsala, Vol. 11, 1912, p. 288.

explained by gravitative differentiation. The outside collar of pulaskite is thought to represent the salic pole of an early magmatic splitting in the vent. Somewhat later the heavier essexite magma, the femic pole, was thrust upward, displacing the pulaskite in the axial portion of the vent[1] (Fig. 120).

Chemical Contrast of Plutonic Rock and Corresponding Effusive Type.—As noted in Chapter II, an effusive magma is usually richer in silica, soda, and potash, and poorer in iron oxides, lime, and magnesia than the corresponding deep-seated rock belonging to the same clan. This important fact is illustrated in Table II. The chemical contrasts between the respective pairs of rocks are explained by the special conditions at a volcanic vent of the central type. As just noted, such a vent is a place of special concentration of magmatic gases. These fluxes lower the freezing temperature of the lava, thus tending to lengthen the temperature interval in which the femic constituents may individualize. For a second reason gravity has special efficiency in differentiating the lava column; a central vent generally has many alternations of dormancy and activity, often passing through the temperature interval (just above the point of complete freezing) where individualization of the femic minerals takes place. On account of their higher specific gravity, the early-formed substances, whether in the solid or liquid phase, must sink in the lava column which, in its upper levels, becomes more salic than the original plutonic magma. An actual surface flow at a surface vent generally comes from the upper part of the lava column. The general chemical relation of plutonic and affusive in each clan seems, in fact, to be a strong evidence of density control in differentiation.

Differentiation in Laccoliths and Intrusive Sheets.—Many thick laccoliths and sheets show tellingly not only the reality of large-scale assimilation but also the nature of the differentiation processes in primary and syntectic magmas. The following table (XIV) lists more than seventy injections, mostly sills and laccoliths. In twenty-nine of them the control of gravity is evident and it has probably characterized six others at least. In most cases the available evidence suggests that the units assembled by gravity were liquid fractions, nonconsolute at the moment of differentiation. The splitting is suggestively analogous to that seen in the stratified arrangement of colloids in water which has stood undisturbed for some months.[2]

Gravitative control over the differentiation is indirectly illustrated in the upward transfer of some of these fractions, including aplitic

[1] F. D. Adams, Jour. Geology, Vol. 11, 1903, p. 281.

[2] Cf. R. S. Symmonds, "Our Artesian Waters," Sydney, N. S. W., 1912, pp. 42–50.

TABLE XIV.—SILLS AND LACCOLITHS ILLUSTRATING PETROGENESIS

Locality	Character of body	Length, *Km.*	Maximum thickness, *M.*	Significant country rocks	Character of differentiation	Rock-species differentiated
1. Sudbury, Ontario.	Interformational sheet.	65	3000+	Huronian sandstone, conglomerate; pre-Huronian gneiss and schists.	Gravitative...	*a.* Micropegmatitic granite and granodiorite, quartz diorite. *b.* Abnormal intermediate types *c.* Norite. *d.* Sulphide ores.
2. Gowganda Lake, Ontario.	4 sills.........	?	15–150	Huronian and argillite, quartzite, conglomerate; pre-Huronian schists and granite.	Locally gravitative.	*a.* Micropegmatite and soda-aplite. *b.* Diabase and gabbro with soda-aplite veins (syenite as differentiate in Lost Lake sill cutting slate.)
3. Cobalt Lake district, Ontario.	Sills..........	30+	150+	Ditto..............	....	Diabase and micropegmatitic diabase, with spots, dikes, and irregular masses of soda-aplite.
4. Pigeon Point, Minnesota.	Sheet (dike ?)	8+	200+	Animikie argillite and sandstone.	Probably gravitative.	*a.* Micropegmatitic granite ("quartz keratophyre"). *b.* Abnormal intermediate types. *c.* Olivine diabase.
5. Duluth, Minnesota.	Laccolith......	200	6000+	Animikie argillite and sandstone; pre-Animikie gneiss, schists, etc.	Gravitative...	*a.* Micropegmatite, granite, syenite. *b.* Anorthosite, gabbro, norite. *c.* Femic norite, pyroxenite, dunite, magnetite ore.

TABLE XIV.—SILLS AND LACCOLITHS ILLUSTRATING PETROGENESIS.—*Continued*

Locality	Character of body	Length, *Km.*	Maximum thickness, *M.*	Significant country rocks	Character of differentiation	Rock-species differentiated
6. Bad River, Minnesota.	Laccolith......	80+	2800+	Same as for No. 5.	Gravitative ?..	Granite (??). Gabbro.
7. Moyie River, British Columbia.	Four or more sills.	9+	10–320+	Beltian (latest pre-Cambrian) quartzite and silicious argillite.	Gravitative...	*a.* Abnormal, micropegmatitic granite. *b.* Intermediate types. *c.* Hornblende gabbro.
8. Cranbrook district, B. C.	Several sills...	?	?	Ditto..............	Gravitative...	Ditto, with local phases of normal diallage gabbro.
9. Near Bonner's Ferry, Idaho.	Sill (with similar sills).	?	240	Beltian argillite, sandstone.	Gravitative...	*a.* Granodioritic type. *b.* "Diorite" (hornblende gabbro ?).
10. Flathead River, Montana.	Sill...........	?	?	Ditto..............	Gravitative...	*a.* Micropegmatitic granite. *b.* "Diorite" (hornblende gabbro ?).
11. Wishards Peak, Idaho.	Sill...........	33+	?	Ditto..............	....	Diabase, gabbro, "basaltic" phase, interstitial micropegmatite.
12. Palisades, New Jersey.	Sheet.........	160	300+	Triassic sandstone, shale.	Gravitative...	*a.* Diabase with micropegmatitic phase. *b.* Olivine diabase.
13. Preston, Connecticut.	Laccolith......	10	1000+	Undated quartz schist, hornblende schist.	Gravitative...	*a.* Oligoclase granite. *b.* Quartz-hornblende gabbro. *c.* Gabbro.
14. Near Lake Wettern, Sweden.	Sills ("beds").	?	?	Almesåkra shale, sandstone, quartzite.	?	Diabase and micrographic quartz diabase.

TABLE XIV.—SILLS AND LACCOLITHS ILLUSTRATING PETROGENESIS.—*Continued*

Locality	Character of body	Length, *Km.*	Maximum thickness, *M.*	Significant country rocks	Character of differentiation	Rock-species differentiated
15. Angermanland, Sweden.	Sills..........	?	?	Pre-Cambrian sandstone, granite.	?	Olivine diabase and micrographic quartz diabase.
16. Kilsyth-Croy district, Scotland.	"Laccolith." ..	5+	100+	Carboniferous sandstone, limestone, etc.	Gaseous transfer.	Basaltic diabase, micropegmatitic quartz diabase, soda aplite and micropegmatite veins.
17. British Guiana.	Sills and laccoliths.	?	?	Thick sandstone, conglomerate (undated).	?	Diabase, augite granophyre (micropegmatite).
18. Bushveldt, Transvaal.	Laccolith......	400	?	Pretoria sandstone, etc.; Black Reef quartzite, argillite, etc.	Gravitative...	*a.* Granite, generally micropegmatitic. *b.* Norite, gabbro. *c.* Pyroxenite, magnetite ore, chromite ore.
19. Insizwa Mt., East Griqualand.	Cross-cutting sheet.	30+	900	Karroo sandstone, shale.	Gravitative...	*a.* Norite and gabbro with micropegmatitic segregations and veins of microgranite. *b.* Olivine norite and olivine gabbro. *c.* Peridotite and sulphide ores.
20. Pretoria district, Transvaal.	Sills..........	?	?	Pretoria sandstone, shale.	?	Diabase or dolerite with micropegmatitic phases.
21. Natal.	Sill...........	?	?	Undated sandstone...	?	"Basalt" and micropegmatitic "hybrid rock."
22. Sinni Valley, Italy.	Laccolith......	?	300+	Eocene argillites, limestone, etc.	Gravitative...	*a.* Granite, aplite. *b.* Plagioclasite. *c.* Gabbro. *d.* Serpentine (peridotite).

TABLE XIV.—SILLS AND LACCOLITHS ILLUSTRATING PETROGENESIS.—*Continued*

Locality	Character of body	Length, *Km.*	Maximum thickness, *M.*	Significant country rocks	Character of differentiation	Rock species differentiated
23. Port Orford quadrangle, Oregon.	Laccoliths ?...	?	?	Cretaceous sandstone, shale; pre-Cretaceous argillite, phyllite, etc.	?	Gabbro with dacitic phases.
24. Shinumo, Arizona.	Sill...........	?	280	Unkar sandstone, argillite, limestone.	Gravitative...	*a.* Syenite. *b.* Diabase.
25. Globe district, Ariz.	Sills and irregular masses.	?	?	Paleozoic shale, limestone, quartzite, etc.	?	Syenite. Diabase.
26. Electric Peak, Yellowstone Park.	Sill...........	?	9	Undated shale.......	Gravitative...	*a.* Feldspathic (shoshonitic phase). *b.* Augitic (absarokitic phase).
27. Thunder Bay, Ontario.	Sills..........	?	Up to 150	Animikie argillite....	?	Diabase, anorthosite.
28. Glamorgan township, Ontario.	Laccolith ?....	13	?	Pre-Cambrian amphibolite and limestone.	Gravitative...	*a.* Gabbro with anorthositic phases. *b.* Pyroxenite, hornblendite, iron ores.
29. Morin district, Quebec.	Laccolith ?....	80+	?	Pre-Cambrian gneiss, limestone, etc.	Gravitative...	Anorthosite with quartzose phases. Gabbro (subordinate).
30. Chibougamau district, Quebec.	Laccolith ?....	45+	?	Keewatin greenstones.	Probably gravitative.	*a.* Anorthosite, gabbro. *b.* Basic norite, pyroxenite, iron ores.
31. Bergen district, Norway.	Laccolith......	40	?	Pre-Cambrian gneiss, granite, and schists.	?	Anorthosite, with pyroxenite and titanic iron ores.
32. Island of Skye, Scotland.	Sills..........	?	?	Tertiary basaltic lavas and agglomerates.	....	Anorthosite in banded gabbro.

TABLE XIV.—SILLS AND LACCOLITHS ILLUSTRATING PETROGENESIS.—*Continued.*

Locality	Character of body	Length, *Km.*	Maximum thickness, *M.*	Significant country rocks	Character of differentiation	Rock species differentiated
33. Island of Rum, Scotland.	Sills	?	?	Basic volcanics		Allivalite, peridotite.
34. Natal and Zululand.	Sills	?	?	Permian sediments		Dolerite, anorthosite.
35. Shonkin Sag, Montana.	Laccolith	5	45	Cretaceous and older shale, sandstone, limestone.	Gravitative	*b.* Syenite. *c.* Transition types. *d.* Shonkinite. *a* and *e.* Leucite-basalt porphyry (last a chilled phase).
36. Square Butte, Montana.	Laccolith	5	350+	Ditto	Gravitative	*a.* Syenite. *b.* Shonkinite.
37. Ice River, British Columbia.	Irregular laccolith.	5+	400+	Cambrian limestone, argillite, etc.	Gravitative	*a.* Sodalite syenite. *b.* Foyaite, urtite, ijolite, jacupirangite, pyroxenite.
38. Lugar, Scotland.	Sill	5.5	42	Carboniferous and older limestone, argillite, sandstone, etc.	Gravitative	*b.* Theralite rich in analcite. *c.* "Picrite." *a* and *d.* Teschenite (chilled phase above and below).
39. Inchcolm Island, Scotland.	Sill	0.8+	20+	Shale and sandstone (age?).		Teschenite, picrite.
40. Benbeoch, Ayrshire.	Sill	?	?	?	Gravitative	*a.* Femic theralite (kylite). *b.* "Kylite-picrite."
41. Castle Craigs, Ayrshire.	Sill	?	?	Carboniferous shale, sandstone, limestone, marl.	Gravitative	*a.* Nephelite teschenite. *b.* Hornblende teschenite. *c.* "Picrite."

TABLE XIV.—SILLS AND LACCOLITHS ILLUSTRATING PETROGENESIS.—*Continued*

Locality	Character of body	Length, *Km.*	Maximum thickness, *M.*	Significant country rocks	Character of differentiation	Rock species differentiated
42. Howford Bridge, Ayrshire.	Sill..........	?	?	Permian lavas and Carboniferous limestone, shale, etc.	"Probably" gravitative.	*a.* Analcite syenite. *b.* "Essexite-dolerite."
43. Cnoc-na-Sroine (Loch Borolan), Scotland.	Laccolith......	6+	400+	Cambrian limestone, Moine schists, Lewisian gneiss.	Gravitative...	*a.* Quartz syenite. *b.* Quartz-free syenite. *c.* Nephelite syenite, borolanite, ledmorite.
44. Lurcombe, Devon.	Sill..........	?	42	Carboniferous shale, limestone, sandstone; Devonian limestone.	?	Augitic teschenite, camptonitic teschenite.
45. Ilimausak, Greenland.	Irregular laccolith ? (composite).	15	?	Sandstone, granite...	Gravitative...	*a.* Arfvedsonite granite. *b.* Quartz syenite. *c.* Pulaskite. *aa.* Foyaite (chilled phase?). *bb.* Sodalite foyaite. *cc.* Naujaite. *dd.* Lujavrite and kakortokite.
46. Kola peninsula, Lapland.	Laccolith......	75	1000+	Paleozoic sediments; gneiss.	Gravitative in part?	*a.* Lujavrite, urtite, etc. *b.* Chibinite, etc.
47. Prospect Mt., New South Wales.	Laccolithic sheet.	2.5	100+	Triassic shale, Permo-Carboniferous sediments.	Gravitative...	*a.* Essexite with soda-aplite veins and segregations. *b.* Femic essexite.

Note.—In the last column the italic letters show the order of superposition of the rocks in the gravitatively differentiated injections.

and sodalitic magmas, which have risen in the chamber with the aid of magmatic gases. Even thick laccoliths of the Henry Mountains type —highly viscous and relatively cool at the time of injection—will not be expected to show pronounced gravitative splitting in place.

At least sixty species of igneous rocks, besides transitional and hybrid types, are represented in the list. All of the plutonic families quantitatively important in the world—granite, granodiorite, diorite, gabbro, anorthosite, syenite, foyaite, peridotite—are represented; and, in addition, many of the rarer families—analcitic and leucitic types, essexite, theralite, teschenite, urtite, ijolite, jacupirangite, lujavrite, shonkinite, borolanite, magnetite ore, chromite ore, sulphide ore, etc. This great range of magmatic types is a principal indication of the significance of these injections for petrogenic theory.[1]

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[1]See note at end of Table XIV.

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22. C. Viola, Bol. R. Com. geol. d'Italia, Vol. 23, 1892, p. 105.
23. J. S. Diller, Port Orford folio, U. S. Geol. Survey, 1903.
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25. F. L. Ransome, Prof. Paper, 12, U. S. Geol. Survey, 1903, p. 85.
26. J. P. Iddings, Mon. 32, Pt. 2, U. S. Geol. Survey, 1899, p. 82.
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31. C. F. Kolderup, Bergens Museums Aarbog, 1903, No. 12.
32. A. Geikie and J. J. H. Teall., Quart. Jour. Geol. Soc., Vol. 50, 1894, p. 645.
33. A. Harker, The Natural History of Igneous Rocks, New York, 1909, p. 140.
34. G. T. Prior, Annals of the Natal Museum, Vol. 2, 1910, p. 147.
35. L. V. Pirsson, Bull. 237, U. S. Geol. Survey, 1905.
36. Ibid.
37. J. A. Allan, Abstract of doctorate thesis published by the Massachusetts Institute of Technology, 1912.
38. G. W. Tyrrell, Geol. Mag., Vol. 9, 1912, p. 75.
39. R. Campbell and A. G. Stenhouse, Trans. Edinburgh Geol. Soc., Vol. 9, 1907, p. 121.
40. G. W. Tyrrell, Geol. Mag., Vol. 9, 1912, p. 122.
41. Ibid., p. 76.
42. Ibid., p. 70.
43. S. J. Shand, Trans. Edinburgh Geol. Soc., Vol. 9, 1910, p. 376.
44. H. J. Lowe, Geol. Mag., Vol. 5, 1908, p. 344.
45. N. V. Ussing, Geology of the Country around Julianehaab, Greenland, in Medd. om Grönland, Vol. 38, 1911.
46. W. Ramsay and V. Hackman, Fennia, Vol. 11, No. 2, 1894.
47. H. S. Jevons, H. I. Jensen, T. G. Taylor, and C. A. Süssmilch, Proc. Roy. Soc. New South Wales, Vol. 45, p. 445, and Vol. 46, p. 111 (1912).

Some of the bodies illustrate a principle which seems certain of increasing emphasis, namely, the influence of contact chilling in forbidding differentiation. The contact phase, a more or less continuous shell, thus represents the original magma. The other phases, enclosed by this shell, are the products of its splitting. The development of chilled phases in differentiated sheets has been described by Lewis (Palisades of New Jersey), by Jevons and others (Prospect intrusion of New South Wales), and by the present writer (Moyie and other sills of the Purcell mountains, British Columbia).

The writer has also suggested a similar explanation for the leucite-basalt porphyry enclosing the syenite and shonkinite of the Shonkin Sag laccolith.[1] The middle of this body shows a section described by Pirsson as follows:

[1]Memoir No. 38, Geol. Survey of Canada, 1912, p. 772.

	Thickness in Feet
a. Leucite-basalt porphyry	5
b. Dense shonkinite	5
c. Shonkinite	5–6
d. Transition rock	3
e. Syenite	25–30
f. Transition rock	15
g. Shonkinite	60–75
h. Leucite-basalt porphyry	15
Total	140 (nearly)

Pirsson has calculated the approximate average composition of the laccolith, with the result shown in Column 3 of Table XV. Column 4 gives the composition of the leucite basalt abundantly extruded in the Highwood Mountains. Columns 1 and 2 respectively show the compositions of the syenitic and shonkinitic differentiates.

TABLE XV

	1	2	3	4
SiO_2	50.0	47.9	48.0	48.0
Al_2O_3	19.4	12.1	12.4	13.3
Fe_2O_3	3.9	3.5	3.5	4.1
FeO	2.7	4.8	4.7	4.2
MgO	2.2	8.6	8.3	7.0
CaO	5.0	9.4	9.2	9.3
Na_2O	3.6	3.0	3.0	3.5
K_2O	8.5	5.6	5.8	5.0

As already stated, Pirsson explains the various rock-types by a combination of crystallization, thermal convection, and settling-out. The influence of convection seems to be an unnecessary postulate. An alternative conception of the differentiation is suggested by the chemical nature of the average rock in the laccolith. Let it be assumed that a leucite-basalt magma, such as elsewhere in the region forms volcanic masses, was here injected. On all contacts of the laccolith, though particularly at its rim, this magma froze quickly. The interior part, much longer fluid, was cooled until it reached the temperature of liquation or the temperature of initial crystallization. Then the settling-out of phenocrysts or (preferably) of the corresponding units of liquation caused the density stratification, with syenite overlying the other pole of differentiation, namely, shonkinite.

The small chemical difference between shonkinite and leucite basalt would make it very hard to prove that the "shonkinite" shells of *b* and *c* in Pirsson's section do not really form a granular continuation of shell *a*. All three shells seem, in fact, to represent the original magma, which has differentiated in the center of the laccolith, giving shells d, e, f, and g. The analyses of b and c have not been published, but in any case their analyses would fall within the limits of variation assignable to leucite basalt.

The same explanation of the likewise celebrated Square Butte laccolith is feasible, though the loss of its roof by erosion makes a final test of the hypothesis here impossible. Tyrrell has conceived a similar mechanism for the Lugar sill of Western Scotland, in which

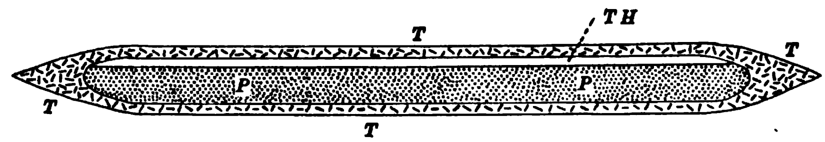

FIG. 121.—Diagrammatic, longitudinal section of the Lugar sill, Scotland. (After G. W. Tyrrell, Geol. Mag., Vol. 9, 1912, p. 75.) *TH*, theralite; *T*, teschenite; *P*, picrite. The sill illustrates gravitative differentiation and the forming of chilled phases. Length, 3.5 miles; thickness, 140 ft.

picrite and various phases of teschenite are associated (Fig. 121). This sill is about 140 feet thick. The rock phases are listed as under:

		Specific Gravity
Upper one-fourth of sill.	*Top marginal phase*—black, "basaltic teschenite"	....
	Teschenite, coarse, highly analcitic	2.64
	Teschenite, normal	2.70
	Teschenite, camptonitic	2.98
	Teschenite, monchiquitic	2.99
5/8 of sill	*Picrite*	3.01
Lower one-eighth of sill.	*Teschenite*, camptonitic	2.81
	Teschenite, normal	2.77
	Basal phase—black, "basaltic teschenite"	....

The original magma was here a teschenite. It was chilled at the contacts, giving "sharp margins of basalt, both at the top and bottom." Strongly analcitic teschenite ("theralite") and picrite are the poles of the gravitative differentiation in the interior.[1] Still another example, on a great scale, seems to be found in the gabbro-anorthosite mass in the Adirondack Mountains (Fig. 122).

As a rule the chilled phase at the roof merges into the salic phase of gravitative differentiation. This relation has often been incorrectly described as "contact basification." The difficulties inherent in the application of Soret's principle or of the principle of fractional crystallization are seen to have given needless trouble in petrology.

[1] G. W. Tyrrell, Trans. Geol. Soc. Glasgow, Vol. 13, Part 3, 1909, p. 298; Geol. Mag., Vol. 9, 1912, p. 75.

In general, the larger a body the more advanced is gravitative splitting. The huge Bushveldt, Duluth, Sudbury, Ilimausak, Chibougamau, and Morin bodies have been respectively split into highly salic and highly femic submagmas, developed on the large scale. The thinner Purcell, New Jersey, Natal, Scottish, and Aus-

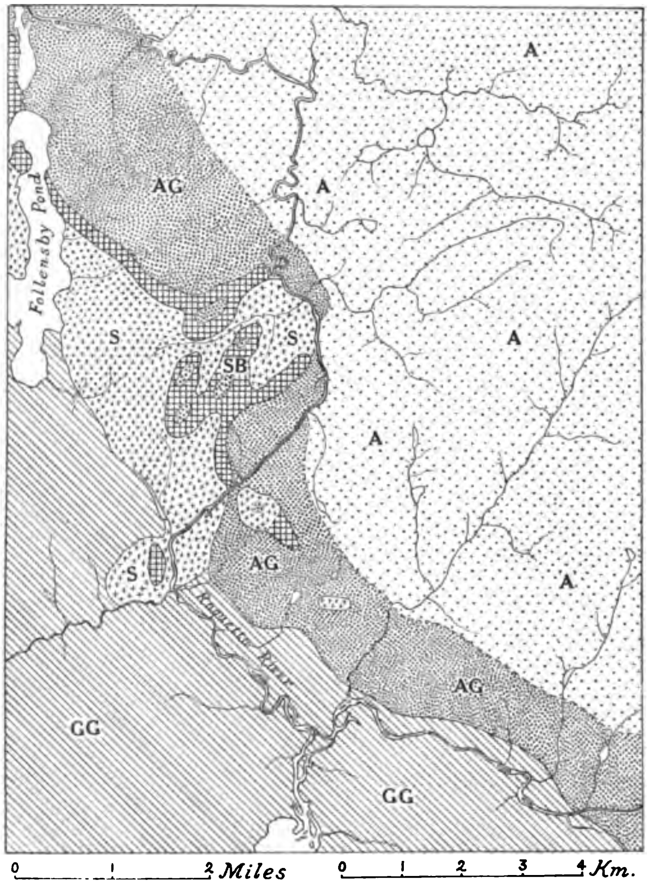

FIG. 122.—Map of part of the Long Lake quadrangle, New York. (After H. P. Cushing, Bull. 115, N. Y. State Museum, 1907.) *GG*, Grenville series limestones and gneisses); *A*, anorthosite; *AG*, gabbroid contact phase of *A*; *S*, syenite; *SB*, bɐsic phase of the syenite. *AG* appears to be a chilled phase of *A*.

tralian injections are less thoroughly differentiated. This rule suggests the reason for the salic and homogeneous nature of normal batholithic rocks.

On the other hand, some of the thinner sheets are more or less drastically differentiated. Those at Shonkin Sag, Square Butte, Ice River, Lugar, and Cnoc-na-Sroine (Loch Borolan) show that alkaline *magmas* must have relatively low viscosity in spite of rapid chilling and in face of experimental proofs that many artificial alkaline *melts* are highly viscous. The contrast suggests that these natural magmas have been specially charged with volatile fluxes—a conception supported by the mineralogy of alkaline rocks and one clearly implied in the hypothesis that these magmas are derivatives of sedimentary syntectics.

The published descriptions of most of the igneous bodies listed in the table illustrate the "freezing-in" or "fixing" of small masses of one differentiate in the crystallized equivalent of its complementary magma. Thus, the micropegmatitic roof differentiate in a Purcell, Sudbury, Minnesota, or South African sheet always overlies a gabbroid or diabasic phase carrying interstitial micropegmatite or schliers or "veins" of the same material. These have evidently been trapped during the solidification of their respective hosts. A large-scale parallel is found in the "transition" or "intermediate" rocks in differentiated injections. Sills and laccoliths evidently throw light on the origin of many plutonic, hypabyssal, and volcanic species which are found only in small volumes.

The anorthosites of the world are best regarded as differentiates of gabbroid (basaltic or. diabasic) magma. The positions of the anorthosite masses in the Duluth laccolith and the Thunder Bay sills suggest some degree of gravitative control over the splitting. The described field relations of the large Bergen, Morin, Glamorgan, and Chibougamau bodies strongly indicate their laccolithic nature. In each of them the anorthosite is specially developed at or near the roof, while pyroxenites, hornblendites, peridotites, or iron ores are found at or near the floor. The writer has, in fact, come to suspect that all anorthosite occurs in injected bodies of the sill, laccolith, chonolith, or dike type, and that even the enormous masses found in Quebec, Labrador, New York State, Norway, etc., are similarly not to be regarded as "bottomless" batholiths. Combining the facts known about the anorthosites, and especially considering the bodies listed in the foregoing table, the most promising hypothesis remains that the larger masses are gravitative differentiates of gabbroid (basaltic) magma. The relatively minute masses found in the banded gabbros of Skye and other regions, and as schliers in many small bodies of gabbro, are clearly local differentiates "frozen in" before gravity could assemble them in thicker sheets. Sills and laccoliths of pure anorthosite amply show that the splitting has often taken place in depth, before injection at visible levels. (See p. 321.)

Because of their limited supply of heat, most sills and laccoliths have not assimilated important amounts of their country rocks. Yet the flat shape and great horizontal extension of many of these intrusives (all originally of basaltic composition) prove low magmatic viscosity, which means some degree of superheat. Large superheated injections must dissolve the invaded rocks to some extent. There is a tendency toward the formation of a chilled phase in the magma, whereby the country rock is protected against assimilation, but this tendency may be checked by the stirring of the magma during injection, by magmatic stoping, by "two-phase convection," and at the roof by the rise of volatile fluxes. All of these conditions are likely to affect such enormous bodies as the Sudbury sheet, the Bushveldt laccolith, and the Duluth laccolith. The chemical character of the invaded formations is obviously important; if they are calcareous or notably hydrous, the fluxing of the original magma at contacts is facilitated. The available field data show that the feeders of sill or laccolith are comparatively narrow. The passage of the original, hot magma through these channels must take considerable time, and thus allowance should be made for possible assimilation during as well as after injection. In the writer's opinion, all of the non-basaltic (non-gabbroid) rocks in the bodies tabulated have originated in syntectics. Faith in this conclusion cannot be won from the study of concordant injections alone, but it is significant that a considerable number of these are described as having been active solvents of their country rocks. Such is the case for the following:

Sudbury sheet (A. P. Coleman).
Pigeon Point sheet (W. S. Bayley and A. C. Lawson).
Moyie and other Purcell sills (R. A. Daly).
Bonner's Ferry and Flathead River sills (F. C. Calkins).
Duluth laccolith (N. H. Winchell and others).
Insizwa sheet (A. L. du Toit).
Natal sills (W. Anderson; *see* G. T. Prior in bibliography above).
Ångermanland sills (A. G. Högbom).
Kilsyth-Croy laccolith (G. W. Tyrrell).
Prospect intrusion (H. S. Jevons and others).
Gowganda Lake sills (N. L. Bowen).

The greatest laccolith on record—that in the Bushveldt—has in its upper levels a vast development of "red granite" which is a strict homologue of the "red rock" of the Duluth laccolith. The argument for a secondary origin of these salic differentiates is strong, as it so thoroughly accords with the proofs of secondary "red rock" or micropegmatite at Pigeon Point, Sudbury, and the Moyie river.

The analcitic phases of the sills at Teschen, which are partly diabase and partly teschenite, can be accounted for by the interaction of diabasic (basaltic) magma on the invaded basic hydrous sediments.[1] An analogous explanation is suggested for the analcitic rocks in the sills at Lugar, Inchcolm, Benbeoch, Castle Craigs, and Howford Bridge; and for the leucitic phase of the Shonkin Sag laccolith. Elsewhere the writer has published the thesis that the foyaitic types of Ice River and Cnoc-na-Sroine (Loch Borolan), as well as the alkaline types at Square Butte, Shonkin Sag, etc., are differentiates of syntectics in which the invaded limestones have played an important rôle.[2] It may be noted that the induction on which that hypothesis was based has been greatly strengthened by a more recent, more complete survey of the world's alkaline-rock terranes. As shown in Chapters XVIII and XIX, similar statistics go far in favoring the idea of sedimentary control during the formation of syenitic and granodioritic magmas.

In general, the tabulated sills and laccoliths illustrate a principal deduction from the assimilation hypothesis: the silica content and related chemical features of the roof differentiate should vary with the chemical nature of the rock assimilated. The salic phase of a Moyie sill (cutting thick quartzites) is an abnormal granite; that of the Shinumo area (cutting shales, limestone, and sandstones) is a syenite; that of the Port Orford intrusives (cutting dominant argillite with sandstone) is a dacite of granodioritic composition. Limestone control is suggested in the leucitic and nephelitic differentiates above noted. The special effects of resurgent water (that absorbed from sediments) has already been found in the analcitic differentiates and in the commonly developed soda-aplites and albitic veins of many of these injections.

Gravitative Differentiation in Stocks and Batholiths.—The differentiation phenomena of concordant injections have been considered at some length because of their supreme importance in the batholithic problem. From their very nature the floorless chambers, in which most of the world's magmas have originated, can only be understood by indirect reasoning. If gravitative splitting and gaseous transfer have been responsible for the phases of sill or laccolith, they may fairly be considered as controlling differentiation in subjacent bodies. Owing to its colossal size and consequently longer magmatic life, a batholith should contrast with any sill in showing more advanced differentiation. Hence, hybrid rocks in batholiths are rare and the homogeneity of their salic and femic submagmas is great; more often than with sills is syntexis completely masked.

[1] See V. Uhlig's section in "Bau und Bild Oesterreichs," Vienna and Leipzig, 1903, p. 898.

[2] R. A. Daly, Bull. Geol. Soc. America, Vol. 21, 1910, p. 87.

Because of the shallowness of the depths reached by erosion, the batholithic outcrop must always exhibit the rock formed near the chamber roof. The femic submagma of gravitative splitting lies too deep for exposure except as it is expelled upward as dikes cutting the country rocks or the already solidified, salic phase of the batholith. The rarity of such late injections and the danger of confusing them with emanations of other primary abyssal wedges mean that useful observations are almost wholly to be confined to the salic phase.

In this connection the petrogenic theory so far outlined has some chief consequences which may be checked by field observations.

a. The primary basaltic wedge is increasingly affected by syntexis, generally leading to a mixture more silicious than basalt. The new,

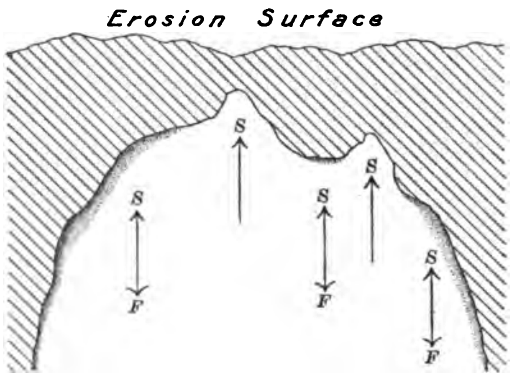

Fig. 123.—Diagrammatic section illustrating the development of femic contact phases in batholiths. *Dotted areas,* femic phase; *blank area,* normal rock of the batholith; *cross-lined,* roof and wall rocks. Double-headed arrows show directions of movement of salic (*S*) and femic (*F*) units of differentiation after crystallization of the chilled contact phase. Single-headed arrows represent the upward movement of salic material transferred by magmatic gases.

mixed magma undergoes progressive differentiation. If a succession of satellitic bodies are erupted from the wedge into levels accessible through erosion, these bodies should, as a rule, be derived from the upper part of the wedge; and hence formed in the order of increasing acidity. Such is the usual observed order, as shown in the table of Appendix B, and briefly considered in Chapter IV. The average succession is thus a powerful argument for gravitative control in the largest of intrusive bodies.

b. The salic differentiate should tend to vary chemically with the character of the average country rock assimilated. We have just seen that this principle affects the nature of the differentiates in sills and laccoliths. The succeeding chapters are largely engaged in showing that it also actually affects the subjacent bodies.

c. Toward the end of its long life the magma of stock or batholith becomes nearly or quite incapable of further assimilation. The partially differentiated syntectic is chilled at roof and wall and there solidifies. Inside this contact shell the still fluid magma continues to liquate gravitatively. Therefore, at the levels reached by erosion the internal part of the mass should be more salic than the chilled phase

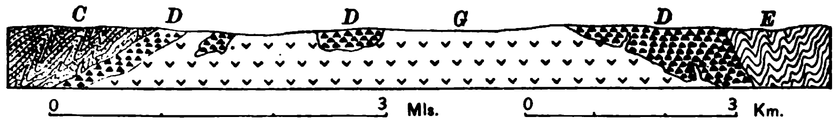

FIG. 124.—Syngenetic granite and diorite in the Penobscot Bay quadrangle, Maine. (After Penobscot Bay Folio, No. 149, U. S. G. S., 1907.) *E*, Ellsworth schist—Cambrian or pre-Cambrian; *C*, Castine volcanics—Cambrian?; *D*, diorite and gabbro—Devonian?; *G*, granite—Devonian? The diorite appears to be an older, chilled phase of the batholith in which the granite later differentiated and invaded the diorite.

(Fig. 123). Herein we have an explanation of most basic contact rocks in subjacent bodies. As with the sills and laccoliths, it is no longer possible to attribute such phases to "contact-basification," produced by diffusion operating on Soret's principle.

d. The solidified contact phase has often been intruded by the central, residual liquid. Such renewed eruptivity may be due to massive

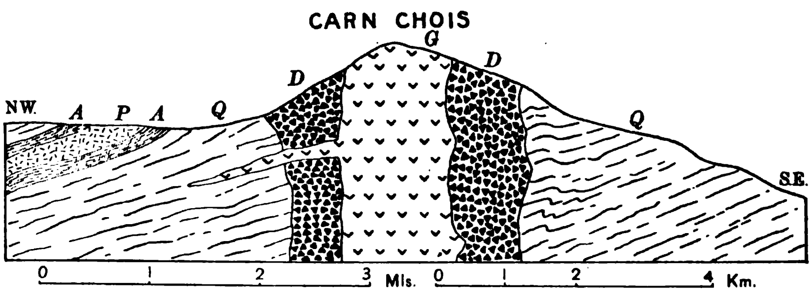

FIG. 125.—Section of the Grampian Hills stock. (After the Government map of Scotland, 1893, Sect. 2.) *Q*, quartzite, etc.; *P*, porphyrite; *A*, amphibolite; *D*, diorite; *G*, granite. Petrogenic relations probably the same as for batholith of Fig. 124.

readjustments in the batholithic chamber or to the corrosive power of the now differentiated liquid magma, which is not chemically in equilibrium with the already chilled, solid rock (Figs. 124 and 125).

The same process is probably represented in wide dikes, where the interiors are often more salic and less dense than the respective contact phases (Fig. 126). The general theory implies, in fact, that a batholith is a *modified dike* of enormous size, a main abyssal wedge which was *initially injected.*

Expulsion of Residual Magma.—Harker has suggested another kind of gravitative control in differentiation.[1] He writes:

"Any differentiation which depends on the sinking of crystals under gravity belongs necessarily to a somewhat early stage of crystallization, when the bulk of the magma was still in a liquid condition. At a later stage, when the crystals formed are so numerous or so large as to touch and support one another, the condition may be likened to a sponge full of water; and it is easy to picture a partial separation being effected by the *straining-off or squeezing-out of the residual fluid magma* from the portion already crystallized. That such a process does in fact take place is amply proved by the phenomena of pegmatites, which represent the final residual magma of plutonic intrusions."

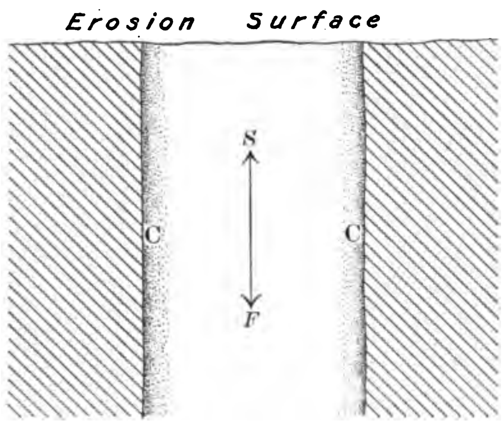

FIG. 126.—Diagrammatic section illustrating differentiation in some dikes. After crystallization of the chilled phase, *C*, gravitative splitting of salic (*S*) and femic (*F*) units continues in the middle of the dike.

The squeezing-out is regarded as specially noteworthy if the freezing magma is subject to pressure from movements of the earth's crust.

Gas and Vapor Differentiates.—Magmatic gases are in origin partly juvenile, partly resurgent. (See page 249.) The vesiculation of surface lavas, the explosive activity at volcanic vents, the activity of fumaroles, and the phenomena of many mineral veins, are obvious proofs that magmatic differentiation affords gaseous or vaporous, as well as liquid products. In a sense the ocean is the largest visible body of "magma" or "rock," probably in greatest part antedating the primitive crustification of the earth. The origin of atmosphere

[1] A. Harker, Natural History of the Igneous Rocks, 1909, pp. 323–327.

and ocean is ultimately a problem in the origin of the igneous rocks.

Gaseous Transfer.—Mere gravitative differentiation in liquid magma cannot explain certain small, basic or ultra-basic phases in intrusive bodies. Contact segregations of magnetite, ilmenite, mica, hornblende, tourmaline, etc., are often found. There is growing belief that these are generally due to upward transfer by emanating gases. (See Chapter XXI.)

CHAPTER XIII

MECHANISM OF VOLCANIC VENTS OF THE CENTRAL TYPE

Introduction

The larger part of volcanic literature deals with the activities at cone and crater. Extensive and intensive as these studies have been, the number of memoirs treating of *all* the essential problems of central eruptions is very small. Yet every general theory of volcanic action must undergo the test of such a thorough questionnaire. This applies to the hypothesis that all vulcanism is a result of the abyssal injection of primary basalt. The following argument will be clearer if a preliminary list of the specific problems relating to central eruptions be reviewed. The list includes:

1. The localization and opening of the vent.
2. The persistence of a principal vent for many thousands of years.
3. The intermittent character of the eruptivity, including (*a*) the alternation of active and dormant phases, and (*b*) the pulsatory or geyser-like quality of eruption during the active stage.
4. The origin of the heat which, by radiation in active craters, is lost in stupendous quantities.
5. The normal evolution of a vent as illustrated in (*a*) explosiveness, and (*b*) the nature of the lava emitted.
6. The mechanism of lava outflow at central vents.

In the present chapter, which is essentially a reprint of part of an earlier publication, these questions will be briefly considered.[1]

Some Direct Consequences of Abyssal Injection

The estimate of 40 kilometers for the average depth of the surface of the substratum may be wide of the mark, but it will serve as the numerical basis for a statement of certain immediate effects of injection.

First, basaltic magma, rising from such depth nearly to the earth's surface, must undergo an average expansion ranging between 1.5 and 6 per cent.[2] A small part of this expansional energy may be directly available for opening fissures in the shell of compression, with consequent extrusion at the surface or development of laccolithic or other bodies within that shell.

[1] Cf. R. A. Daly, "The Nature of Volcanic Action," Proc. Amer. Acad. of Arts and Sciences, Vol. 47, 1911, pp. 67–108 and 119–122.

[2] See Amer. Jour. Science, Vol. 22, 1906, p. 201.

Secondly, abyssal magmatic injections vary in solvent power, according to their own volume and degree of superheat, and according to the chemical nature and temperature of their wall rocks. The primary basaltic wedges are thus divisible into the two, assimilating and non-assimilating, classes. Recognition of this fact is of deep import to volcanic theory.

Thirdly, magma which has been forced from the substratum level to levels where the pressure is 10,000 atmospheres less, must have completely altered conditions of equilibrium for the juvenile gases. These include hydrogen, sulphur gas, carbon monoxide, carbon dioxide, chlorine, nitrogen, and other gases, elementary or in combination. The theory of physical chemistry indicates that the dissolved volatile constituents must, in such a case, slowly diffuse upward, in order to reestablish equilibrium. There is thus a tendency to saturate and then supersaturate the upper part of the magma with juvenile gases; if by the mere change of pressure the magma is supersaturated with one or more of the gases, bubbles must form and these must slowly rise. If the injected body is tightly roofed, the gases continue to rise until the growing gas-tension at the upper levels stops diffusion.

Genetic Classification of Volcanic Gases

It will conduce to clearness if a brief statement is here made as to the absolute necessity of distinguishing the different classes of volatile materials which are associated with igneous activity. These fluids are either *magmatic* or *phreatic.*[1] Phreatic fluids are of atmospheric or oceanic origin, and include *vadose* waters, and also those which Lane has called *connate* (contemporaneous) waters, because trapped in sediments at the time of their deposition. As indicated by Suess, explosions due to the heating of phreatic fluids by intrusive magma have occurred without the ejection of true lava, either fluent or pyroclastic.

Magmatic fluids are those actually dissolved in magma or emanating therefrom. Those of primary origin and reaching the earth's surface for the first time are of the *juvenile* class. The magmatic fluids of secondary origin, that is, those absorbed from country-rock formations, have been called *resurgent.*[2] Resurgent fluids may enter the magma either as constituents of assimilated country-rock or by independent solution.

Although only magmatic fluids are important in the present connection, it is useful to review, in tabular form, the whole group of gases and vapors which are engaged in volcanic and subvolcanic activities.

[1] Cf. E. Suess, Das Antlitz der Erde, Bd. 3, 2te Hälfte, Wien and Leipzig, 1909, p. 655.

[2] R. A. Daly, Amer. Journ. Science, Vol. 26, 1908, p. 48.

Magmatic fluids (volcanic; internal).	Juvenile	Emanations directly from abyssal injection.
		Emanations from primary solid abyssal country-rock.
	Resurgent	Vadose and connate fluids absorbed in the syntectic process.
		Vadose fluids absorbed independently of rock assimilation.
Phreatic fluids (subvolcanic; external)		Vadose.
		Connate.

The resurgent fluids may possibly do something toward keeping a vent open, but their volatilization means the partial lowering of temperature in the magma, so that their abundance in a conduit implies a certain "damping of the fires" already accomplished. In basaltic volcanoes assimilation of the normal, acid crust-rocks has evidently not been important; at such vents the juvenile emanations are clearly in control from beginning to end of each volcano's history. This statement does not conflict with the fact that resurgent water, either vadose or connate with sediments, is often responsible for the explosions at basaltic and other volcanoes. The clearing-out of the explosion funnel, which is always shallow and superficial, is not so vital to continued activity as the preservation of fluidity in the magma of the conduit.

Opening and Localization of the Vent

Enlarged Fissures.—The events of 1783 at the famous Laki fissure of Iceland illustrate the close relation between some central eruptions and the pronounced fracturing of the surface rocks of the earth. For much or all of its length the master crack was doubtless connected with a typical, narrow, abyssal injection. Many hills of the cone-and-crater type were built along the fissure, which emitted floods of basalt on the greatest scale recorded by man. Escape of lava from the abyssal injection was evidently much easier at some points along the visible fissure than at others. The case is analogous to the formation of the "Dewey craters" (cinder cones) on the Mauna Loa lateral fissure opened in 1899, and of scores of similar accumulations on the flanks of Mauna Loa, Etna, etc. Dutton[1] gives this

[1] Sixth Ann. Rep. U. S. Geol. Survey, 1885, p. 172. Other famous examples are the cone-chains built in the zone of the African Great Rift (J. E. S. Moore, Tanganyika Problem, London, 1903, pp. 80 and 89; J. W. Gregory, The Great Rift Valley, London, 1896, p. 216 and maps); the lines of vents opened on the Etna fissures mapped by Silvestri; the Nicaraguan cone-chain, mapped by K. von Seebach.

explanation for some of the necks occurring in the well known Mount Taylor district of New Mexico. In all such instances certain *points* in the fissure-lines are favored in the eruptivity, while the remainder of each fissure was either never opened clear to the surface, or else was rapidly sealed up by congealing lava (Fig. 100).

The continuance of eruption at any point depends on victory in the *struggle with cold.* That victory in its turn depends in part on a sufficient width of vent to permit of a column of lava which is not chilled too greatly by conduction into the wall rock. Since erupting fissures are never more than a few meters in width at the surface, it seems necessary to postulate a widening of each fissure where it carries cone and crater of prolonged activity. The widening may be conceived to depend on four different factors: solution and mechanical removal of

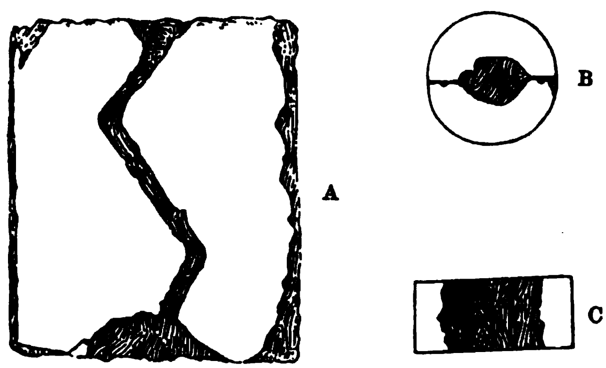

Fig. 127.—Artificial diatremes in granite cylinders. (After A. Daubrée, Bull. soc. géol. France, t. 19, 1891, p. 317 ff.) *A* and *C* are sections; *B* is an end view of cylinder; all three after explosion.

wall rock by emanating lavas; melting and explosive abrasion of the wall rock by magmatic gas emitted *through* the lava column. It is not important here to decide on the relative efficiency of these processes in merely enlarging the original fissure to full vent size. Their relative efficiency becomes of fundamental significance in the problem of the persistence of eruptivity at a central vent. In the following discussion of this topic it is concluded that the vent is kept hot, and therefore active, because of the emanation of free juvenile gas rising from great depth—a process which may be styled "gas-fluxing." Since a great enlargement of an original fissure, below the bottom of any possible explosion funnel, demands much time, it would follow that most of the enlargement is due to gas-fluxing. Gaseous explosion and erosion of the walls by emanating lava might be more effective in the widening of smaller and more short-lived vents.

It is an easy step from the observed case where central eruptions are developed on fissures of lava-flooding, to the case of the formation of central vents on surface fissures from which no true fissure-eruption has ever taken place. Such a crack may be too narrow to permit the extrusion of gas-free lava, which, through quick chilling, seals the fissure, and yet the crack may be wide enough to allow passage of the juvenile gases from an underlying abyssal injection. Entering the crack under pressure and therefore at high temperature, these gases must tend to enlarge it by slow fusion of the wall rock. The process may or may not be supplemented by the opening of an explosion funnel at the surface. As the vent is enlarged by gas-fluxing the magma rises within it, and, kept open by the emanating gas, permits of further upward blowpiping.

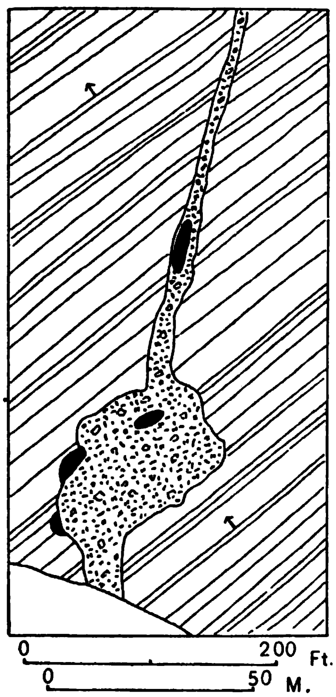

FIG. 128.—Diatreme opened on a fissure, Laws Castle, Fifeshire. (After A. Geikie, Geology of Eastern Fife, 1902, p. 218.) Lines show Carboniferous sediments traversed, with indication of dip. *Dots*, agglomerate of sandstone, shale, ironstone, lapilli, fragments of olivine basalt; *solid black*, basalt.

This mechanism implies that the original surface fissure may not be discernible by the geologist. It may correspond to no vertical or horizontal displacement, and at the surface itself be no wider than an ordinary master joint or fault fracture. Enlarging slowly downward, such a fissure might be charged with accumulating gases so far as ultimately to cause an explosion. Since the gases must tend to accumulate about one or more points along the fissure, the explosion form will be that of a vertical tube surmounted by a funnel.

Diatremes.—The resulting vent is a *diatreme*, the formation of which was so successfully imitated by Daubrée (Fig. 127). This type of diatremes is, then, located on a surface fissure, which may or may not be continuous with the abyssal fissure of the primary injection (Fig. 128). These considerations show the difficulty of disproving the existence of through-going crustal fissures beneath central vents. Some volcanic diatremes may be formed in homogeneous, unfissured rock, and a second type, a pure explosion form, should be recognized in a full classification of vents.

A diatreme of either kind may be enlarged by the continued passage of the blowpiping gases, by the mechanical erosion of the walls by outflowing lava, or by the piecemeal stoping of the walls by the lava column. In some cases the last-mentioned process may be more important than pure explosion itself.

Plutonic Cupolas.—Lastly, a complete genetic scheme should recognize a process of vent-opening which is neither explosion, nor the enlargement of through-going fissures.

The rise of batholithic magma is differential. Partly because of gas control its attack on the roof is most efficient at *points*, rather than along lines or in large areas (Fig. 129). This deduction seems well matched by the field fact that round intrusive bosses or small stocks

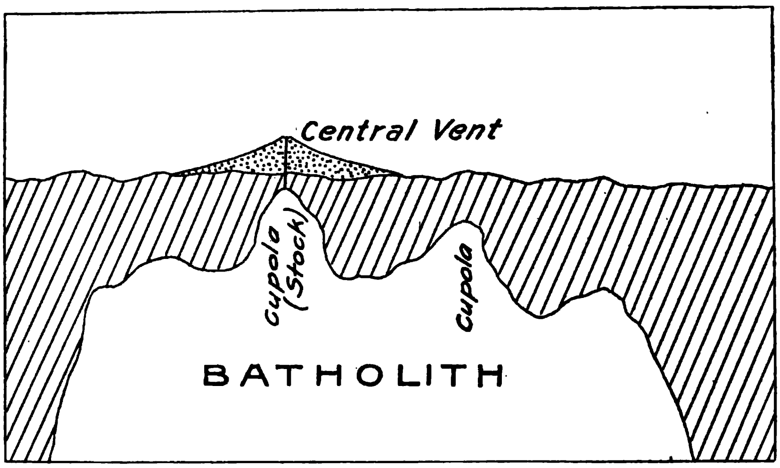

FIG. 129.—Ideal section showing formation of volcanic vent through the differential rise of assimilating magma.

are characteristic cupola forms on large batholiths. Some of these bosses have been proved to have very steep contact-surfaces and, in shape, as in thèir cross-cutting relations, closely simulate volcanic necks. It is evident that every such cupola increases as well as localizes the danger of true volcanic action. Blowpiping fusion or pure explosion may destroy the relatively thin roof above the cupola. The resulting vent is, then, of composite origin. Its upper part is like the two simple types of central vents already described. Its lower part is neither diatreme nor blowpiped hole, but represents the work of all the agencies of magmatic assimilation in depth. This composite type of vent illustrates the close connection between volcanic and plutonic geology.

The original location of each first-rank vent is thus explained by the roof topography of the underlying magma chamber. Some one of the cupola-like offshoots of the fluid magma, where it penetrates the solid rock above, must become a place for the accumulation of the rising gases. A vent once formed at the top of the cupola, it must tend to persist as a vent throughout the period of magmatic fluidity. Other vents from the same chamber may be opened, but must have shorter lives, because of the drawing away of the juvenile gases toward the more favored vent. (Fig. 133, p. 270.)

Continuance of Activity at Central Vents: Analysis of Conditions at Kilauea

Left to itself, the lava column of a vent must soon freeze and activity must cease. Yet there are abundant proofs that the lives of many

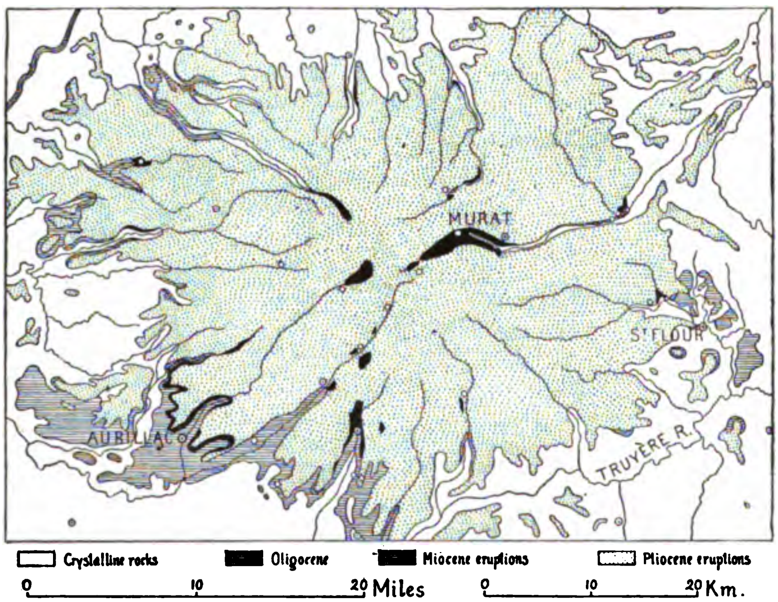

Fig. 130.—Map showing the long continuance of volcanic action at the Cantal, France. (After M. Boule, Bull. serv. carte géol. France, No. 76, 1900, p. 29.) The eruptions occupied part of Miocene and Pliocene time.

central vents have been prolonged for great periods of time. The example of the Cantal volcano may be recalled (Fig. 130). Long-continued activity is conditional on victory in the struggle with cold. How is the victory attained? How is the heat of the underlying magma chamber transferred to the narrow vent? Hawaiian vents supply data on this fundamental question. Though Kilauea may be the vent of a satellitic injection (see p. 294), the mechanism is doubtless the same as for a vent over a main abyssal injection.

Rate of Heat Loss through Conduction into the Walls.—It is possible to obtain a rough idea of the enormous rate at which heat is given out, by conduction and radiation, at Kilauea (Fig. 131). Actual calculation will show that radiation is much more responsible for the

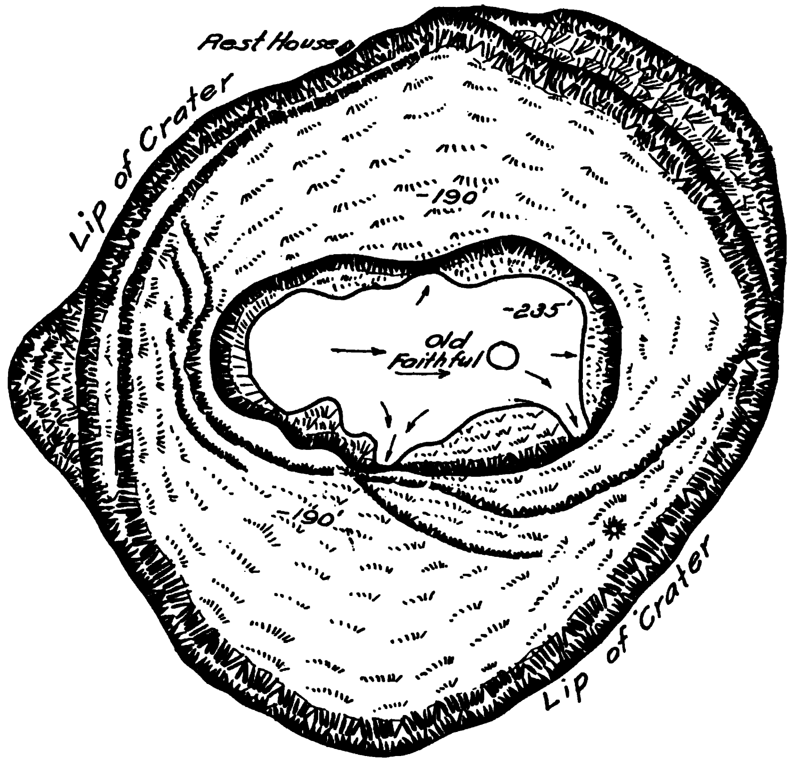

FIG. 131.—Map of Halemaumau crater, Hawaii, in July, 1909. (After J. M. Lydgate assisted by the author.) Arrows indicate the general trend of the lava currents during that month. The positions of the "Old Faithful" lava fountains and of the more important caves eroded by the liquid lava in the "Black Ledge" are shown. Figures show the depth (in feet) below the rest house. Scale, 1:5,000.

loss of heat than is conduction into the wall rocks of the vent. To make this point clear it will be assumed that the cross-section of the conduit is throughout as large as the area of the lava lake, though very probably the lake represents a strongly flaring part of the lava column. (See Fig. 132.) The conditions of the lake in 1909, when it was studied by the writer, are assumed. The area of the lake (and therewith the cross-section of the lava column) is considered as circular, with radius of 100 meters. This is more than the superficial extent of the lake in 1909 but less than its average extent since 1820. The cylindrical pipe with the uniform cross-section is assumed to extend to a depth of 2 kilometers, where it opens out into the great feeding chamber.

Let the temperature of the magma be assumed as 1200° C.; and let the average original temperature of the rocks now forming the conduit walls be assumed as 40° C. Two hundred and fifty years after the conduit was first opened and henceforth occupied by lava at the uniform temperature of 1200° C., the rate of flow of heat through

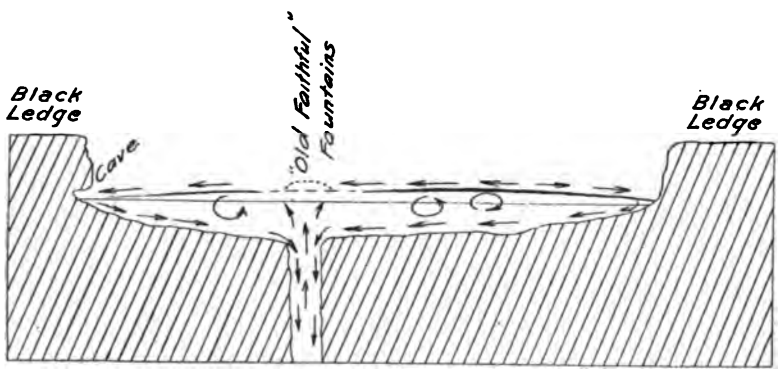

FIG. 132.—Diagrammatic section of Halemaumau, illustrating two-phase convection, erosion of caves, and vortical action. The lava "scum" is represented by the heavy black line at the lake surface. Length of section about 300 meters. Thickness of scum exaggerated.

the walls would be nearly uniform; and 12 meters from the contact of the molten lava the temperature of the wall rock would be about 1115° C.[1] This estimate is based on the assumption that the diffusivity for heat in rock at high temperature has the value given by Kelvin. That value is certainly too high, but the temperature stated for a point 12 meters from the contact would in any case be reached after some centuries following the establishment of the lava column. An idea of the heat loss by conduction may now be obtained. The equation for heat flow is:

$$Q = k.A.\frac{T-T_1}{x}.t,$$

where k is the coefficient of conductivity, A the area of the surface traversed, x the thickness of the plate traversed, t the time, T and T_1

[1] R. A. Daly, Amer. Jour. Science, Vol. 26, 1908, p. 23.

the steady temperatures of the two sides of the plate. In this case we may use C. G. S. units, with k 0.005 (certainly too high a value for these temperatures), t one second, x 1200, and A $2\pi r \times 200{,}000$. We have

$$Q = .005 \times 2 \times 3.14 + \times 10{,}000 \times 200{,}000 \times \frac{1200-1115}{1200} \times 1$$
$$= \text{approximately } 4{,}450{,}000 \text{ gram calories.}$$

The result expresses the approximate amount of heat lost by conduction into the wall rock during each second.

Rate of Heat Loss through Radiation at the Crater.—Siegl has recently supplied a datum required for estimating the heat lost by radiation from the surface of the lava lake. The general equation is

$$\log S = \log c + \varepsilon \log T,$$

in which S represents the number of calories radiated per second, T is the absolute temperature stated in degrees Centigrade, and c and ε are constants. For basalt Siegl has found that $c = (10)^{-12} \times 0.589$, and $\varepsilon = 4.083$.[1] His experiments show that the equation holds for basalt up to 472° absolute. It is very probable that it may be applied, with relatively small, or at least non-significant, error, to basalt at the higher temperatures and under the conditions of radiation represented at Kilauea. Such extrapolation gives the following results:

$t°$ C.	$T°$ abs.	S.
450	723	0.277
727	1000	1.044
1000	1273	2.800
1200	1473	5.082

In 1909 the present writer used a Féry pyrometer to determine the average temperature of the non-incandescent scum which regularly covered at least two-thirds of the lava lake. The average temperature for this part was estimated to be about 450° C.; the corresponding heat loss is computed to be 0.277 cal. per square centimeter per second.

At the best points of observation in 1909, the area of the hottest lava was not large enough to cover the "black spot" of the pyrometer for a time long enough to give a reading for its full temperature. It was clear, however, from the behavior of the galvanometer needle during the brief exposures of the very hot lava in the "Old Faithful fountains," that its temperature was well above 1000° C. From the color the temperature of the hottest lava visible in the lake was esti-

[1] K. Siegl, Sitzungsber. Akad. Wissen. Wien, Math.-Naturw. Klasse, Bd. 116, 1907, p. 1203.

mated to be not far from 1200° C. The third of the lake relatively free from scum was estimated to have an average temperature of 1000° C., corresponding to a heat loss of 2.8 calories per square centimeter per second.

With radius of 100 meters the circular lake would lose in heat about 375,000,000 calories per second. The actual lake of 1909 probably lost more than 230,000,000 calories per second.

We may conclude that heat was then being lost by radiation more than fifty times faster than by conduction into the walls of the Kilauean pipe, if it be assumed as 2 kilometers deep. It would seem that radiation at the crater must be the dominant one of these two phases of heat loss in any strongly active volcano.

Methods of Heat Transfer.—The upward transfer of heat into a volcanic pipe might conceivably take place in five different ways: (1) by explosive removal of material from the upper part of the vent, followed by the uprise of magma from the still fluid chamber; (2) by simple overflow of magma at the lip of the crater; (3) by thermal convection in the lava column; (4) by a process which may be called, for convenience, "two-phase convection"; and (5) by the passage of free juvenile gas *through* the lava column, thus bringing abyssal heat to the upper part of the vent.

The first and second processes have obviously played no essential rôles in keeping up the heat supply in Kilauea since 1823, when detailed records of its activity began.

Mere thermal convection can hardly be regarded as an essential factor in postponing the solidification of a lava column. In this matter the analogy with water heated from below should be applied only with due attention to quantitative values. The degree of superheat in the actual well-established vents is not indefinitely high; it is doubtless no more than 200° or 300° C. If convection be lively enough to keep the column molten, the maximum thermal-density differences within the vent itself should certainly be less than those corresponding to a difference of 100°. A temperature change of 100° C. means a density change in magma of less than one-half of one per cent.[1] The density change in water as it passes from 4° C. to 100° C., or vice versa, is about 4.3 per cent. With a density difference about one-tenth that of water in the same temperature interval, and with that difference distributed through kilometers of depth instead of through decimeters, as in the ordinary convective experiment with water, the convective potential in the lava column is evidently of a very low order. Moreover, the speed of the convection depends on the viscosity of the magma, which through chilling and through pressure is doubtless, on

[1] According to Barus, as quoted in Amer. Jour. Science, Vol. 26, 1908, p. 26.

the average, hundreds or thousands of times more viscous than water. It follows that in resistance to be overcome, as in working potential, heat convection must be incomparably less rapid in a volcanic conduit than in artificially heated water.

For example, let us suppose that at the depth of 2 kilometers the conduit passes into the feeding magma chamber; that there the temperature is 1300° C., while the temperature at the surface is 1200° C.; that the average kinetic viscosity of the conduit lava is as low as that of a liquid 100 times more viscous than water; that the thermal convection in the conduit is to be compared in rapidity with that obtaining in water heated from 4° to 100° in a wide tube 1 meter high. The maximum convective gradient for the water system may be expressed as

$$\frac{4.3 \text{ (per cent. expansion)}}{1 \text{ (meter, thickness)}} = 4.3$$

The gradient in the lava column is approximately

$$\frac{.5 \text{ (per cent. expansion)}}{2000 \text{ (meters)}} = .00025.$$

The maximum speed of convection in the water of the imagined experiment is, then, $\left(\frac{4.3}{.00025} \times 100 = \right)$ 1,720,000 or more times greater than that of the lava in the conduit.

It seems certain that such slow transfer of magma could not keep the temperature of surface lava of the lake at anything like the observed point. On the average, every square centimeter of the lake's surface in 1909 radiated about one calory per second or 86,400 cals. per day. Taking .35 as the mean specific heat of basalt (1200°–1300°), this implies a daily heat loss corresponding to a temperature fall of 100° C. in a vertical column of lava more than 2400 meters deep, and 1 square centimeter in area at its upper surface. Evidently, other and much more effective agencies must be at work to keep Kilauea active, year in and year out.

Two-phase Convection.—However, there is a different and very powerful kind of convection constantly illustrated in Halemaumau when that lake is in full activity (Fig. 131). The persistent streaming of the lava into the caves, characteristically developed at the shore cliffs of the lake, is evidently due to surface gradients. In general, the "scum" stands higher in the central part of the lake than it does in the caves and in the channels leading to the caves. The "scum" or thin crust of the lake prevents or retards the escape of the magmatic gases, which accumulate beneath it and form a kind of froth, or emulsion of lava and gas, of relatively low density. The tendency is, thus, to raise the crust in one or more areas. In each cave, because of reflection from its roof, and perhaps also because of special heating through actual combustion of sulphur, hydrogen, and other gases, the crust is rapidly and completely fused. The escape of the gases is there facilitated and the surface of the lava is correspondingly lowered. The surface slopes are, therefore, steepest in the channels leading to the caves, and streaming at the rate of 2 to 5 kilometers an hour may be observed in the channels. Elsewhere the surface slopes are lower and streaming is less rapid. The caves are not outletting tunnels, as so often stated, but each is closed at a distance of a few meters from its entrance. The lava which has streamed into the cave must return to the main part of the lake. Only one way of return is possible, that by a backward sub-surface current. Having lost its dilating gas and grown rapidly denser, the heavy lava sinks and flows toward the center of the lake. Similarly, the ever-changing surface slopes in other parts of the lake compel vertical currents and vortices of the most complex design (Fig. 132). This type of magmatic movement may be called "two-phase convection." It depends on the presence of a liquid "phase" and a gas "phase" in the lava.

If vesiculation of the liquid magma is possible in great depth, two-phase convection may cause a relatively speedy transfer of hot magma to the surface. How effective this process can be is worthy of somewhat detailed statement. The imposing change in magmatic density, which is effected by very slight increase in vesiculation, will first be indicated. The speed at which individual bubbles rise will then be estimated, and, finally, a rough quantitative idea of the convection enforced by the development of gas bubbles in depth will be obtained.

The specimens of Hawaiian pahoehoe lava collected by the writer contain, on the average, at least 200 vesicles per cubic centimeter of the lava. The vesicles of the surface layers are roughly spherical and average no more than 2 millimeters in diameter, though, of course, the range of diameters is very great. For convenience, let a spherical mass of hydrogen, having the radius of 1 millimeter at one atmosphere of pressure and at 1200° C., be called the "standard bubble" for basalt. Extrapolating on Amagat's pressure-volume curves for hydrogen at 1200° C., the volumes and radii for the standard bubble at high pressures may be calculated within a margin of error which is probably very small. Examples are shown in the following table:

Approximate depths in magmatic column (meters)	Pressure in atmospheres	Volume (cm.^{3})	Radius (cm.)
730	200	.000115	.030
3,650	1,000	.000025	.018
7,300	2,000	.000014	.015

Gas-free basalt at 1200° C. and one atmosphere has a specific gravity of about 2.75. On account of the slight compressibility of rock-matter, that value may be assumed as typical for bubble-free basaltic magma at pressures up to several thousand atmospheres. If such magma become charged with 200 standard bubbles per cubic centimeter, at 200, 1,000, and 2,000 atmospheres, the specific gravity falls to the following approximate values (Col. 1):

Pressure (ats.)	Specific gravity	
	1	2
200	2.688	2.7495
1000	2.736	2.74975
2000	2.742	2.74997

A single standard bubble replacing the liquid in each cubic centimeter of bubble-free basalt would lower the specific gravity to the amounts shown, again approximately, in Col. 2.

This last table illustrates possible ranges of buoyancies induced by vesiculation at the three depths chosen. The actual buoyancy attained may often be much higher. It will be seen that the buoyancy produced by only a small extra vesiculation of a local mass of magma must occasion a rapid uprise of that mass.

The bubbles themselves, as independent bodies, must rise with comparative slowness. The experiments of H. S. Allen have shown that small spherical bubbles, rising in a liquid, attain their terminal velocity according to the formula previously deduced by Stokes for the rise of light solid spheres of very small radius.[1]

Let r represent the radius of a bubble; d', its density; d, the density of the surrounding magma; v, the coefficient of viscosity of the magma; g, the acceleration of gravity; and x, the terminal velocity of the rising bubble, that is, the velocity when the motion is steady. The Stokes formula applies if the product dxr is small compared with v. This is clearly true for the standard bubble in liquid basalt with the viscosities appropriate to pressures of 200 to 2000 atmospheres. We have, then,

$$x = \frac{2}{9} gr^2 \left(\frac{d - d'}{v}\right).$$

Computing the values of x when the magmatic viscosity is assumed to be constant and only 100 times that of water at 15° C. (0.0115) or 1.15 in C. G. S. units, we have, at the three illustrative pressures:

[1] H. S. Allen, Phil. Mag., Vol. 50, 1900, pp. 323 and 519; G. G. Stokes, Cambridge Phil. Trans., Vol. 9 (2), 1850, p. 8.

Depth meters)	Pressure (ats.)	Terminal velocity (x)	
		Cm. per second	Meters per hour
730	200	.47	16.9
3650	1000	.17	6.1
7300	2000	.12	4.2

Since experiment shows that the viscosity of a liquid rises rapidly with pressure, it is instructive to assume higher values of v for the greater pressures. If v be taken again arbitrarily as 500 and 10,000 times that of water for magma under the pressures of 1000 atmospheres and 2000 atmospheres, respectively, we have for x these values:

Pressure (ats.)	Viscosity	Terminal velocity (x)	
		Cm. per second	Meters per hour
200	1.15	.47	16.9
1000	5.75	.034	1.2
2000	115.00	.0012	.04

In all cases smaller bubbles would rise more slowly, x varying directly as the square of the radius.

Two important conclusions may be drawn from these computations. Gas bubbles of the "standard" mass or of smaller mass must rise from the deeper levels of an abyssal injection with extreme slowness. In view of the high magmatic viscosity and great pressure in depth, it is conceivable that it may take thousands of years for a "standard" bubble to rise from a depth of, say, 10 kilometers to the earth's surface. This suggests one reason why gaseous emanation is so prolonged at central vents.

Secondly, from the slowness with which bubbles rise, it is clear that a swarm of bubbles, which for any reason have been aggregated locally in special abundance, would be dispersed into the surrounding, less vesiculated magma with great slowness. The local mass of magma thus specially vesiculated would be less dense than the average magma and, as a unit, would rise toward the crater. It now remains to indicate that a very moderate amount of extra vesiculation must cause such a two-phase mass to rise with comparatively great velocity.

Of course, this case has not been investigated experimentally; an indirect method must be used in its discussion and the result can at present hardly be other than qualitative.

Once again to make the mental picture clearer, it is well to assume certain conditions arbitrarily. As an example, let the swarm-filled mass be spherical; let the reigning pressures and magmatic viscosity be as in the foregoing cases; let the surrounding magma have a density of 2.75; and let the extra vesiculation be to the extent of 50 "standard" bubbles per cubic centimeter on the average. The corresponding densities of the sphere are shown in the second column of the following table:

Pressure (ats.)	Sp. gr.	$d-d'$	v (assumed)	R (cm.)
200	2.734	.016	1.15	.52
1000	2.746	.004	5.75	2.40
2000	2.748	.002	115.00	22.25

For solid spheres rising in the magma we may compute the "critical radius" (R), that is, the radius of the largest sphere which would obey the law of the Stokes formula. The values for R, as stated in the fifth column, have been found with the help of Allen's formula:[1]

$$R^3 = \frac{9v^2}{2gd(d-d')}.$$

The terminal velocities of the solid spheres having the critical radii would be, for the corresponding values of R, v, and $(d-d')$, as follows:

$d-d'$	v	R(cm.)	Terminal velocity	
			Cm. per sec.	Meters per hour
.016	1.15	.52	.82	29.5
.004	5.75	2.40	.87	31.4
.002	115.00	22.25	1.88	67.6

The figures show that even for small solid spheres the velocities are considerable. With increase of radius the terminal velocities would at first increase very fast, and then more slowly. However, since the resistance to the motion would, for large spheres, vary with the square of the velocity, neither the Stokes formula nor any other yet developed can declare the actual velocity for large solid spheres moving in the magma.

Nevertheless, Allen's formula for large spheres is of distinct help in guiding one to a proper appreciation of the case. It reads:

$$V^2 = \frac{1}{k} \cdot \frac{4\pi}{3} \cdot gr \cdot \frac{d-d'}{d}.$$

where k is a constant for a given liquid-solid system.[2] It follows that the terminal velocity here varies directly as the square root of the radius and as the square root of the difference of the two densities. Referring to the table showing terminal velocities for solid spheres with

[1] H. S. Allen, Phil. Mag., Vol. 50, 1900, p. 324.

[2] H. S. Allen, ibid., p. 532.

critical radii, it seems clear that, in any of the three cases, spheres of corresponding density and of radii of 10 or more meters would rise at the rate of at least 10 centimeters per second or 360 meters per hour.

This analogy of solid spheres seems to afford some help in our imagining the course of a specially vesiculated mass of liquid magma. The rough quantitative estimate just made for large solid spheres cannot be directly applied to this case. On account of the possibility of internal movements in the rising mass of liquid magma, its speed of uprise will not be quite the same as that of a solid mass of the same shape, size, and density. Yet the correction to be applied is probably small.

As such a mass approaches the surface, through a column of rapidly decreasing viscosity and with a constant increase of buoyancy because of expansion of the contained bubbles, the velocity must greatly increase. However much a given mass of magma might lose buoyancy through the loss of its larger, more swiftly rising bubbles, the total effect must be to generate a powerful upward current in the magmatic column.

In spite of the lack of the necessary, full experimental data, our general conclusion seems to be as follows. Experiment does show that the rise of individual gas bubbles in magma will be very slow. Neither experiment nor theory can as yet declare the actual speed of the rise of a mass of specially vesiculated magma, but the analogy of solid spheres moving under gravity in a liquid enforces the belief that the more buoyant magma will move rapidly if its volume is of the order of thousands of cubic meters. Assuming such differential vesiculation in great depth, and assuming also a mechanism by which the gas of risen magma is dissipated (as in a volcanic vent), two-phase convection must stir the magma column to great depth and with considerable rapidity. Such a process must be incomparably more rapid than that of thermal convection under volcanic conditions. The transfer of heat may readily be conceived as able to supply the radiation loss in the crater for long periods of time.

The basal assumption, that vesiculation occurs at great depth in a volcanic conduit, is necessarily difficult to test by the facts of field geology. During its solidification an intrusive body is likely to be cleansed of its bubbles, which rise, and the gas so collected at the roof is slowly dissipated into the country rock. This may be the explanation of the lack of vesiculation in most dikes, sheets, laccoliths, and batholiths. In general, the rock of a lava neck may be similarly freed from bubbles during the relatively long period of crystallization. Nevertheless, cases are not wanting where bubbles are known to have been trapped in basalt at depths greater than 300 meters. The basalt of the West Maui neck, illustrated in Fig. 136, is charged with many minute vesicles at a depth at least 300 meters below the original top of this lava column. Vesiculation at some depth is proved by the discovery of dikes and sills abundantly charged with gas pores. The writer has recorded vesicular basaltic dikes of the Okanagan mountains and in a sill of the Columbia range, British Columbia. Du Toit has found two such porous sills in the Stormbergen region, Cape Province, South Africa.[1] Rogers and du Toit observed that sandstone xenoliths in an intrusive dolerite sheet of the Karroo have been rendered vesicular by the magmatic heat in spite of the considerable pressure.[2] These and other known examples seem to strengthen the belief that bubbles may form in magma at the depth of several kilometers.

It is important to note that two-phase convection has two distinct, though related causes. Principal stress has hitherto been laid on differential vesiculation in depth, whereby a mass of magma becomes more buoyant than the enclosing magma and rises. Just as inevitably, the magma which is freed of gas at the crater must sink and stir the column to great depth. Even if the column is not vesiculated at all, this second mode of convection is likely to be effective in the vertical transfer of the magma. As a rule, the density of a liquid is lowered by the absorption of hydrogen, nitrogen, oxygen, or other relatively light gas. This is very probably true of natural mixtures of juvenile gases when dissolved in magma. As these gases stream or diffuse from all azimuths in the feeding chamber toward the base of the narrow conduit, they are there concentrated. Thus, the magma *in* the conduit, at its lower levels, attains a density less than that of the average magma of the feeding chamber, and, *a fortiori*, less than that of the gas-freed magma descending from the crater level. This is another kind of density convection depending on the relative concentration of juvenile gas. For lack of experimental data, it is now impossible to estimate the efficiency of this species of convection. It may be a powerful ally of two-phase convection proper. For example, it is conceivable that the upward movement of magma is *begun* in the conduit because of the concentration of gas in solution and not in bubble phase. Then, as the magma rises to levels of smaller pressure, the gas begins to separate out in bubbles and enforces true two-phase convection of ever-increasing speed. In view of these various modes of gas control, the vertical stirring of the magma column may, perhaps, be more safely described

[1] A. L. du Toit, 16th Ann. Rep. Geol. Comm. Cape of Good Hope, 1912, pp. 122–123.

[2] A. W. Rogers and A. L. du Toit, Ann. Rep. Geol. Comm. Cape Good Hope, 1903, p. 39.

as, in general, a gas-concentration convection. Yet the actually observed fact is that at the crater the gaseous phase does separate, in bubble form, from the liquid phase, and the writer has preferred to emphasize this empirical fact in adopting the name "two-phase convection."

Lava Fountains.—Herein the writer believes that we have an essential part of the explanation of "Old Faithful," the site of the greater periodic "fountains" of Kilauea. That circular area, about 20 meters in diameter, has represented the true axis of the lava column for many years, and seems to have been the main source of magmatic heat throughout the known history of Kilauea. In 1909, at average intervals of about thirty-five seconds, the surface of the lava lake in this area was domed up to maximum heights of a few meters. These fountains are not due purely to the rise and explosion of great gas bubbles, the collapse of which could have been readily observed. Very small amounts of gas or vapor were given off at the moment of doming or immediately afterward. The outbursts are best explained, in part, on the principle illustrated in the upspringing of a log of light wood freed at the bottom of a lake. Through its momentum the log may jump clear out of the lake. In part, the outbursts of "Old Faithful" are due to true explosive dilatation of the gas bubbles in the "log." The latter process is doubtless the chief cause of the smaller "fountains" playing over the surface of Halemaumau, and of those which played over the surface of Dana Lake or New Lake twenty-five years ago. The draining of each of these two lakes has shown that it was saucer-shaped and very shallow over most of its area, and the writer believes this is true of Halemaumau to-day. (Compare Fig. 132). The depth is generally much too small to allow of such momentum in magmatic "logs" that they might leap to the heights actually observed. The periodicity of "Old Faithful" is suggestively like the rhythmical, pulsatory action so often observed when a liquid flows against strong friction, as water does in a drain pipe.

The site of "Old Faithful" is, thus, the place where the juvenile gases rise from the depths in two-phase mixture with liquid lava. With the collapse of each dome, the gas-charged magma finds its level and runs under the semi-solid or solid "scum" on the lake surface (Fig. 132). There the gas is slowly freed and accumulates beneath the "scum" until the tension produces a true explosion, that is, one of the many smaller "fountains" so constantly appearing on the lake.

The incessant streaming in Halemaumau, the nature of the "Old Faithful fountains," and the ceaseless vortical motion in the lake, as well as the similar phenomena in the active Mokuaweoweo, are so many direct evidences of two-phase convection, which calculation shows must be rapid, provided slight variations in vesicularity occur in the depths of the lava column. Though it is not possible to prove absolutely that the Kilauean column is vesiculated in depth, it certainly is so at the surface to a remarkable degree. At many points, the lower part of the wall of Halemaumau was found, in 1909, to be covered with thin coatings of black glass which represented splashes of lava from the adjacent lake. This lava almost instantly "froze" to the wall. In every case it was extremely porous, so as to be quite spongy in appearance. The vesiculation was almost if not quite complete before the "splash" struck the wall, and it is simplest to suppose that the surface lava of the lake is a froth. There is no known reason why vesiculation should be the rule at one atmosphere of pressure and non-existent at one hundred or one thousand atmospheres; it is all a question of the degree of saturation with gas. The two-phase convection hypothesis rests on this unproved assumption, but its merit is great, as it explains the essential facts of circulation in Halemaumau.

Cooling by Rising Juvenile Gas.—As a fifth hypothesis it might be conceived that the heat is kept up in the lake through the rise of bubbles of *free* juvenile gas from the magma chamber, the bubbles arriving at the surface with some excess of temperature above that required to give the lava of the lake its observed fluidity. But the feeble explosiveness of the emanating gas at Kilauea shows that any unit mass of it, arriving at the surface, is already nearly expanded to the volume appropriate at one atmosphere of pressure, and therefore that the gas is in nearly perfect thermal equilibrium with the enclosing lava at the surface. Such bubbles, as they rise and expand, must thereby tend to cool the magma.

The cooling effect is very great, as may be shown by the following calculation. In an adiabatic expansion of a perfect gas: let T' be the initial absolute temperature, and T the final absolute temperature; let p' be the initial pressure, and p the final pressure; and let γ $(=1.4)$ be the ratio of the specific heat of the gas at constant pressure to its specific heat at constant volume. Then

$$\frac{T}{T'}=\left(\frac{p'}{p}\right)^{\gamma-1}$$

At about 37 meters below the lake surface the pressure is ten atmospheres. If the bubble, after expanding adiabatically, is to arrive at the surface at a temperature of 1200° C., it must have at the depth of 37 meters a temperature of about 3700° C. (assuming no dissociation of the gas). Evidently the free-moving gases have a cooling effect on the upper part of the lava column.[1] That this effect is actually small is, of course, due to the small mass of gas emitted in a unit of time and to the fact that γ is much less than 1.4 for the actual (not "perfect") gases while rising through the deeper levels. Moreover, it has been noted that the rise of a bubble must be exceedingly slow if its mass is anything like that in the average vesicle of frozen lava. So slow is the transfer that the rapid heat wastage at Halemaumau cannot possibly be compensated by any residual superheat in the emanating gas.

On the other hand, the thermal conditions are different in craters floored with highly viscous lava. There the emanating gases commonly issue at pressures of more than one atmosphere, and they are thus kept hot and endowed with some fluxing power. The small blowholes in Kilauea, as in most other basaltic districts, have long been kept open through this action. It is quite possible that such hot-blasting is operative on a greater scale in larger openings like the crater of Stromboli. Yet even at Stromboli that cannot be the chief method of heat transfer from the depths, and again no other method than that of two-phase convection seems competent to keep the lower and greater part of the lava column fluid. At Kilauea, at the wonderful Mokuaweoweo (the vent of a main abyssal injection), at Matavanu in Savaii, we seem compelled to exclude all other agencies for heat transfer except this type of convection. The same explanation seems to apply also to Vesuvius and Stromboli, for their craters in times of strong activity have been observed at close quarters and, like Halemaumau, they show lava "fountains" and other features of this convection.

The Volcanic Furnace.—So far, no assumption has been made that the heat transferred to the top of the volcanic conduit is other than primary in origin, that is, heat due to the initial temperature of the parent abyssal injection. Such is the orthodox view of volcanic heat. The rough estimate made in the discussion of thermal convection suggests the difficulty of understanding how the mere primary heat suffices to explain the long life of many volcanoes.

It may well be questioned, however, that all the heat at a volcanic vent is primary.[2] That due to the radioactivity of magma during

[1] I. C. White (in the Bulletin of the Geological Society of America, Vol. 24, 1913, p. 280) has recently described the notable cooling of a Pennsylvania gas-well by the expansion of natural gas. At a depth of 6000 feet the temperature was found to be 100° F. instead of 145° F., the value expected from the local gradient and White attributes the anomaly to chilling by a strong gas-flow near the 6000-foot level. On the other hand, the unusually steep temperature gradients found in natural-gas fields may possibly be explained in part by the increase of pressure as the gas is generated under a tight cover.

[2] Cf. G. Tschermak, Sitzungsber. Akad. Wiss. Wien, Vol. 75, 1877, p. 162, where a brief statement is given, showing a clear anticipation of this hypothesis.

the fluid stage of an abyssal injection is too small in amount to affect the rate of heat loss to any sensible degree. More promising is the idea that heat-producing chemical reactions in the conduit may have powerful effect. Since the day when Sir Humphry Davy renounced his own explanation of magmatic heat as due to the oxidation of alkaline metals contacting with water, most volcanic theories have regarded magma as inert so far as exothermic reactions are concerned. On the other hand, recent studies of gaseous emanations from active volcanoes and from artificially heated rocks and meteorites clearly suggest the possibility of such reactions.

Analysis of any perfectly fresh igneous rock shows the presence of water to a considerable percentage by weight. This is true of intrusive gabbros and diabase as well as of basaltic lavas. Most of the non-hygroscopic water determined in the analysis of quite unaltered gabbro or basalt may be as much a primary constituent as the silica or the alumina. We must believe that hydrogen and oxygen, in the proportion characteristic of water, are present in primary basaltic magma. It does not follow that, under volcanic conditions, these elements will issue from the vent in combination as water. In his able monograph on "The Gases in Rocks," R. T. Chamberlin indicates the general reaction to be expected in the Kilauean or other basaltic magma chamber. He writes:

"The effect of pressure on chemical equilibrium is to favor the formation of that system which occupies the smaller volume, but if there is no change in volume, in passing from one system to the other, the increase of pressure presumably has no influence on equilibrium. In the reaction

$$3FeO+H_2O \leftrightarrows Fe_3O_4+H_2$$

considered as a thermochemical equation, the number of gaseous molecules, and hence the volume of gas, always remains the same, so that it is not likely that this reaction will be influenced by change of pressure. A rise of temperature favors the formation of that system which absorbs heat when it is formed. A comparison of the amount of heat liberated by oxidizing three molecules of FeO to Fe_3O_4 and one molecule of H_2 to H_2O shows that, in the former case, 73,700 calories are evolved, and in the latter, 58,300; that is, $3FeO+H_2O \rightarrow Fe_3O_4+H_2+15{,}400$ calories. As heat is evolved in this process, a rise of temperature would accelerate the reaction in this direction less than in the reverse. In other words, the higher the temperature, the more would the formation of ferrous oxide and water be favored as compared with the conditions at lower temperatures.

"Because of this, there is much reason to suppose that, at the depths where lavas originate, hydrogen and oxygen exist combined as water, since up to temperatures of 2000° C., the dissociation of water takes place only to a limited extent. If a state of equilibrium between hydrogen, water, and the iron compounds were established in the heated interior where a magma originated, as soon as it commenced its way upward and began to lose heat the condition of equilibrium would be destroyed. With the falling temperature the tendency to reestablish equilibrium would favor the formation of that system which was produced with the liberation of heat, *i.e.*, magnetic oxide and free hydrogen. In ascending lavas which are losing heat, the tendency, therefore, is to produce hydrogen and magnetite, or ferroso-ferric compounds. This is doubtless an important source for the hydrogen which is so copiously exhaled during a volcanic eruption. At the same time this process accounts for the widespread occurrence of magnetite in igneous rocks."[1]

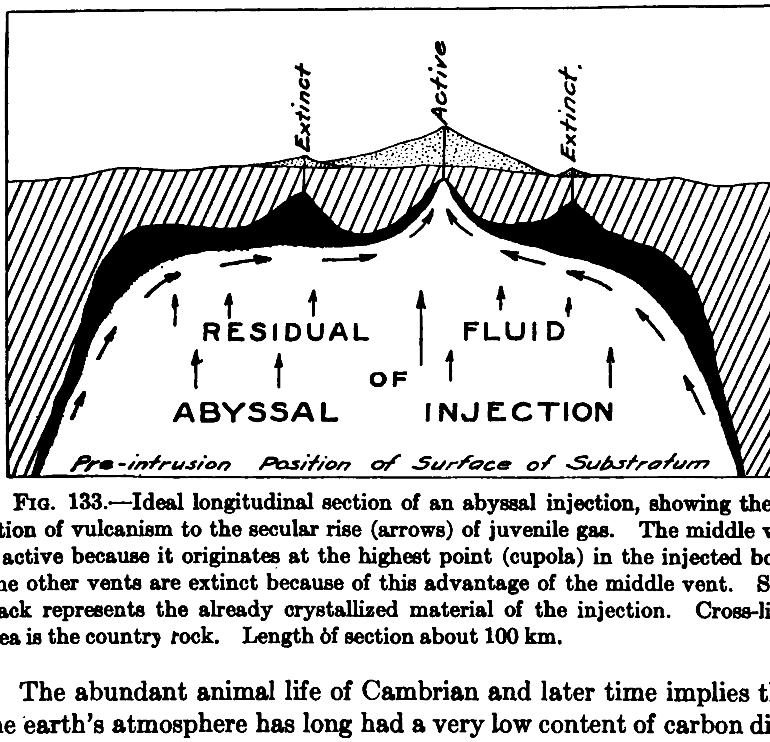

FIG. 133.—Ideal longitudinal section of an abyssal injection, showing the relation of vulcanism to the secular rise (arrows) of juvenile gas. The middle vent is active because it originates at the highest point (cupola) in the injected body. The other vents are extinct because of this advantage of the middle vent. Solid black represents the already crystallized material of the injection. Cross-lined area is the country rock. Length of section about 100 km.

The abundant animal life of Cambrian and later time implies that the earth's atmosphere has long had a very low content of carbon dioxide. The amount of this oxide which has been locked up in the carbonate rocks since the beginning of the Cambrian period is so enormous that most of it, or all of it, must be considered as of juvenile origin. Yet more clearly than in the case of water, carbon dioxide must be regarded as a primary constituent of earth magma. Under the same conditions as those described by Chamberlin, ferrous iron is oxidized to magnetite by carbon dioxide, yielding carbon monoxide and 6000 calories per gram molecule.

[1] R. T. Chamberlin, The Gases in Rocks, Publication No. 106, Carnegie Institution of Washington, 1908, p. 66.

The list of the juvenile gases and vapors also includes nitrogen, chlorine, sulphur, and hydrocarbons. These and other volatile substances, including hydrogen and carbon monoxide, stream from all azimuths in the magma chamber to the lower end of the conduit. The pipe has always a very much smaller cross-section than the feeding chamber, implying some concentration of the volatile matter (Fig.133 and 134). At conduit temperatures this ever-varying mixture of gases must, according to practically infinite probability, be in unstable chemical equilibrium; under the conditions new equilibria are attained with the evolution of heat.

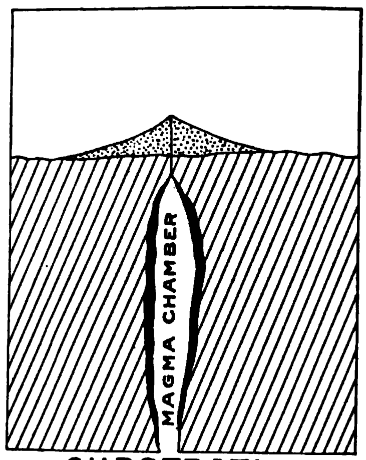

FIG. 134.—Ideal cross-section through middle cone shown in Fig. 133.

The relative proportions of each gas must, in general, be different from that in the primary magma before it was injected. Concentration of the gases means, according to the law of mass-action, the development of new compounds. As the pressure is less in the conduit than in the underlying chamber, the viscosity of the magma is less, the gas bubbles are larger, and the speed of possible reactions is thereby increased.

Of course, the actual amount of heat evolved during the chemical rearrangements in the conduit cannot be estimated, but a glance at the following tables (showing some examples) must assure one that the heat product from the complex system may be of a high order.[1]

HEATS OF FORMATION

Calories per gram-molecule		Calories per gram-molecule		Calories per gram-molecule	
[HCl]	+22,000	[SO_2]	+71,080	[$CaCl_2$]	+190,300
[H_2O]	58,300	[CO_2]	96,960	[K_2Cl_2]	211,220
[H_2S]	5,400	[SO_3]	103,240	[Na_2Cl_2]	195,380
[H_3N]	11,890	[P_2O_5]	369,900	[$FeCl_2$]	82,050
[H_4C]	21,750	[FeS]	24,000		
[CO]	29,000	[CaF_2]	238,800		

[1] The values for the heats of formation and reaction are taken from the works of Thomsen, Muir and Wilson, Nernst, and others. In some cases more recent experiments give slightly different values.

HEATS OF REACTION

$CH_4+2O_2 = CO_2+2H_2O+195,200$ cals.
$CO_2+H_2 = CO+H_2O+9,980$ cals.
$3FeO+H_2O = Fe_3O_4+H_2+15,400$ cals.
$3FeO+CO_2 = Fe_3O_4+CO+6,000$ cals.
$NH_3+HCl = NH_4Cl+42,500$ cals.[1]
$CO+O = CO_2+68,040$ cals.

In addition, there is the possibility that a large supply of energy was potentialized at the high temperatures of the primitive earth and that this energy becomes converted into magmatic heat under the conditions of a volcanic vent. Becker has suggested this in the case of uranium.[2] Arrhenius has proposed the hypothesis that the heat of the sun is supplied principally through the break-up of endothermic compounds.[3] Warren has shown that, at high pressure and temperature, steam is partially converted into the strongly endothermic ozone and hydrogen peroxide.[4] Lines indicating cyanogen are found in the spectra of some stars and comets, and Arrhenius attributes the nitrogen of the air largely to the dissociation of volcanic cyanogen. In the formation of a gram-molecule of this gas, 65,700 calories are potentialized. The dissociation of chlorine involves the absorption of 113,000 calories.[5] Dissociation of other gaseous elements means heat absorption of the same order of magnitude. When ferric oxide and iron sulphide react to form ferrous oxide and sulphur dioxide, 80,640 calories are absorbed. When carbon and carbon dioxide react to produce carbon monoxide, 38,800 calories are absorbed. When steam and C react to form carbon monoxide and free hydrogen, 28,900 calories are absorbed.

In addition to the heat evolved by the dissociation of endothermic compounds, another source of great energy is to be found in the combination of the freed, "nascent" elements with other constituents of the magma. The powerful thermal effect of interaction between hydrogen or oxygen and the carbon or nitrogen atoms of cyanogen hardly needs quantitative statement to show its value.

[1] Though ammonium chloride may not be able to form within the magma column of a volcanic conduit, it does form at the surface, where the loss of heat chiefly occurs. Similarly, ammonia may form from its elements in the relatively cool crust of the lava lake in a crater, also producing heat at the zone of radiation.

[2] G. F. Becker, Bull. Geol. Soc. America, Vol. 19, 1908, p. 146. The final yield of radium is about 2,000 millions of calories per gram, or nearly 250,000 times the thermal value of a gram of carbon burnt in oxygen.

[3] S. Arrhenius, Worlds in the Making, New York, 1908, p. 91.

[4] H. N. Warren, Chem. News, Vol. 77, 1898, p. 192. When 1 gram of oxygen is converted into 1 gram of ozone, 750 calories are absorbed.

[5] M. Pier, Zeit. für phys. Chemie, Vol. 62, 1908, p. 385. Ekholm has suggested that the formation of "elements" may partly explain solar energy.

In this connection it may be noted that the total melting heat of ordinary rock-matter (measured from 0° C.) is only 400 to 450 cals. per gram, and that the latent heat is only about 90 cals. per gram.

Such examples emphasize the value of the conception that abyssal injection, entailing a sharp change of pressure and a slower change of temperature in primary magma, may set free a vast amount of energy which is available for conserving the melting temperature in a lava conduit. Very great superheat is, however, prevented by two-phase convection, which tends to keep the volcanic furnace and the surface lava at nearly the same temperature.

The whole system, as imagined, is somewhat analogous to a modern hot-water plant with an almost perfectly lagged vertical pipe running up from the furnace. Or, again, the generation of heat in the conduit is analogous to that in the gas-mixture of a blowpipe. In the first case (two-phase convection) the rising gas is a passive agent in the upward transfer of heat; in the second case (chemical changes) the gas is a positive heater, thus itself tending to annul or diminish the cooling effect due merely to its own expansion. For a double reason juvenile gas has fluxing power in the vent.

Summary on the Heat Problem of an Active Central Vent.—A volcano of the central-eruption type, like all others, depends on antecedent abyssal injection of magma into the earth's crust, furnishing a magma chamber whence the vent may draw its supply of energy.

Three possibilities are open: (1) The primary magma may have been initially saturated with juvenile gas at the original pressure of 10,000 atmospheres or more. (2) Only the upper part of the magma may be saturated with gas because of the change of pressure resulting from the injection. (3) Or the magma may not be saturated immediately after injection, even at the pressure of one atmosphere.

In the first case, bubbles must form throughout the chamber at all levels above the original depth of the magma. In the second case, bubbles must form at all levels above the lowest one where saturation has been developed by change of pressure. In the third case, bubbles will form only after other causes than mere change of pressure have operated. At least three such causes are conceivable. (a) The upper part of the magma chamber might become supersaturated through the upward molecular diffusion of gases, whereby these are concentrated. This is a reasonable expectation on the general principles of physical chemistry, though experimental or other proofs are lacking. (b) The slow crystallization of the magma might be accompanied by the ejection of gas, as it is actually seen to emanate during the crystallization of artificial slags. That process might cause local supersaturation in the still liquid magma, with the formation of bubbles. (c)

Chemical reactions in the magma, such as the generation of hydrogen from dissolved primary water vapor—a reaction to be expected with a slight fall of temperature—might produce gases insoluble in the magma at the pressure reigning at the place of the reaction.

Among so many possibilities, it seems legitimate to assume the generation of free gas in the main magma chamber. Irrespective of their origin, the bubbles must rise with great slowness through the magma chamber, because, first, they are of small size; and, secondly, because the viscosity of magma under great pressures must be relatively high. Even in the case of supersaturation in all parts of the new abyssal injection, the entire freeing of the bubbles may occupy many thousands of years.

As the bubbles rise, the gas tends to be concentrated in the volcanic conduit. There the laws of mass-action and of the degradation of energy seem to enforce exothermic reactions of the gaseous constituents among themselves and with the elements of the liquid magma. It is most probable that the heat so generated is very great when compared to the mass of matter participating in the reactions. The conduit is thus a furnace where the potential energy of the accumulating gases is converted into heat energy.

Other and perhaps very important sources of heat prolonging the activity of the volcano are: (a) the conversion of the potential energy of liquid components of the magmatic system when thrown out of chemical equilibrium by the change of pressure and subsequent lowering of temperature; (b) the liberation of latent heat in the slow crystallization at the walls of the magma chamber; and (c) some degree of initial superheat in the magma, perhaps of the order of 100° or 200° Centigrade.

Since the loss of heat at an active vent is chiefly due to radiation at the crater, the continuance of activity is controlled by the efficiency of the mechanism by which the heat of the main chamber and the heat chemically generated in the conduit are transferred to the earth's surface. Field observations at Kilauea and elsewhere, along with *a priori* deductions, have suggested the general dominance of two-phase convection (or, more generally, convection due to systematic, local changes in gas-concentration) in making this transfer.

Juvenile gas is thus conceived to act in a two-fold capacity—as a positive heater (its chemical reactions tending to annul the cooling due to expanson) and as the agent enforcing convection. Its net effect is to keep fluid the top part of the lava column during the volcano's activity. The conception as a whole may therefore be called the *gas-fluxing* hypothesis. For vents occupied by highly fluid lava this hypothesis as just stated seems to suffice. For craters floored with more viscous lava, the emanating gas issues under more or less high pressure and may function as a melting blast, making more perfect the analogy with an artificial blowpipe.

Revival of Activity at the End of a Dormant Period

One of the leading problems in vulcanism relates to the periodicity of central eruptions. This also seems to find explanation on the gas-fluxing hypothesis. We have seen that the accumulation of gas bubbles in the conduit must be a very slow process. So long as the vent is open, the escape of the gas from the magma is specially facilitated. That is true, not because the pressure on the main part of the lava column is less than in times of dormancy, but because of the rapid freeing of gas into the open air, with the consequent rapid production of heavy, gas-freed lava which sinks and thus hastens the two-phase convection. The tendency is, therefore, sooner or later to exhaust the gas concentrated at the lower end of the conduit. With sufficient removal of the heat-producing and heat-transferring agent, the forces of cold temporarily win in the never-ceasing struggle and the lava solidifies at the surface; a plug of greater or less thickness is formed. The crater may become temporarily so dead that even solfataric action ceases and a forest may flourish within the crater, as has been the case with Vesuvius.

On account of the small horizontal dimensions of the average vent, the consolidation of such a lava plug may be completed in a few years. This new rock is characteristically tough; when cooled, it is the strongest rock in the average volcanic cone. In the text-books on dynamical geology and in special vulcanological memoirs, the removal of the plug is usually stated to be due to simple explosion of the gases accumulating below it. Yet it is obvious that in the normal cone, which is largely built of loose ash deposits of very low tensile strength, the weakest place in the pile is on its flank and not at the main central plug. By the orthodox view, therefore, the new crater, the main one for the succeeding period of activity, should have a different location from that of the earlier main crater. The fact is, that, in very many cases, the main vent is located at the same place through the many different periods of activity of the greater cones. The beautiful symmetry of a Fujiyama or of a Mayon is the result. The removal of the plug at the close of a dormant period is clearly not the mere mechanical result of explosion. There must be a preliminary weakening of the plug, and apparently the only cause for that weakening is to be found in the fluxing by juvenile gas.

First we may consider the case where the terrestrial forces keep the liquid column supported in the conduit. With the formation of the plug, the loss of heat falls to a very low rate as compared with that ruling in the active period. Until the plug is removed, nearly all the loss is due to conduction and is very slow. Two-phase convection is slowed down, but the rise of bubbles does not cease nor does the volcanic furnace cease working, since a renewed concentration of juvenile gas is begun. To that positive source of heat in the conduit is to be added the heat developed by the compression of the gas as it accumulates beneath the plug and as it is squeezed by any upthrusting of the magmatic column due to crustal movement. Gradually the lowest part of the plug becomes liquefied, preferably along its vertical axis, where the heat inherited from the last active period preserves the line of maximum temperature in the whole upper part of the volcano. The reliquefied lava sinks into the column, dissolving some of the accumu-

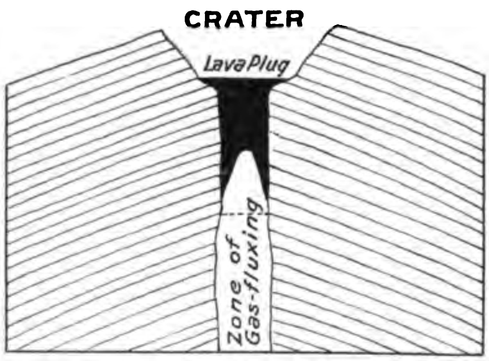

FIG. 135.—Section of upper part of a dormant cone, showing some progress in gas-fluxing. The broken line in the middle of the vent shows the original depth of the solid plug.

lating gas, so that heat of solution is probably to be added to the other supplies which tend to threaten the existence of the plug. Hence, at least three processes co-operate in fusing the plug; these are: heat of chemical reaction, heat of gas compression, and heat of gas solution. As the plug is thus weakened, the gas-tension increases and activity is renewed by one or more major explosions, shattering the remaining part of the plug (Fig. 135).

Though full experimental data for the testing of these conclusions are not yet in hand, it is not difficult to see that the fluxing power of even small masses of juvenile gas is great under these conditions. If chemical reactions supply any large fraction of the heat lost by radiation in the active period, they must raise the temperature of the lava column under conditions of dormancy. This involves a slow melting of the country rock, and especially the plug.

In most cases dormancy is ended by explosions so powerful as to show pressures under the plugs of even higher order than the pressures in the greatest modern cannon at the moment of discharge. These pressures run well over 2000 atmospheres. If a given plug, when frozen to maximum thickness, is 1000 meters deep, the initial pressure on the gas first collecting beneath it would be about 270 atmospheres. Amagat's experiments furnish the data from which the temperature effect of the adiabatic compression of the typical gases, carbon dioxide and hydrogen, may be approximately computed.

At the request of the writer Professor H. N. Davis has kindly deduced the thermodynamic equation for these two cases. If T_0 is the initial temperature; T, the final temperature; p_0, the initial pressure; and p, the final pressure, we have

$$T = T_0\left(\frac{p}{p_0}\right)^n,$$

in which n is an exponent approximately determined from Amagat's curves. If the initial temperature and pressure are, respectively, 1273° C. absolute and 270 atmospheres, and the final pressure is 2700 atmospheres, the average value of n for carbon dioxide is about .17; and, for hydrogen, n probably lies between .26 and .31. For carbon dioxide the computed value of T is 1880° absolute, and for hydrogen 2300° to 2600° absolute. This adiabatic compression of carbon dioxide would develop heat to the amount of about 200 calories per gram. Similar compression of pure hydrogen would develop an amount of heat ranging from 3000 to 4000 calories per gram. The compression of the gaseous mixture actually formed under volcanic plugs would produce heat to amounts intermediate between those calculated for carbon dioxide and for hydrogen. Since hydrogen is one of the most abundant constituents of the mixture, it is possible that adiabatic compression of the mixture, under the conditions above described, would produce at least 1000 calories per gram of gas. Since the latent heat of holocrystalline igneous rock is about 90 calories (Vogt), this heat of compression could fuse more than 10 grams of rock per gram of gas.

Calculation further shows that if the compression of a considerable volume of gas be isothermal, other conditions being as above assumed for the adiabatic compression, the heat produced is of the same large order of magnitude.

As the lower part of the plug is fused, the liquid sinks through the gas-rich part of the magma column, so that the fluxing gas is always in immediate contact with the solid rock. Since the solid plug retains a relatively high temperature inherited from the last active period, and since the vertical axis of the plug is the hottest part of the volcanic cone at all levels above the top of the lava column, it is clear that fluxing will be most rapid along the axis.

Again, a local development of heat is to be expected as the re-fused rock, which had been largely freed of gas in the last active period, begins to absorb the gases collecting in the conduit. Nothing is known as to the solution heat of any juvenile gas as it is absorbed in a natural magma. In each case it is practically certain to be positive and it may be important in amount. The data for the same gases when dissolved in water have some value in the way of analogy. The following table is taken from Thomsen's Thermochemistry:

Vapor or gas dissolved in water	Heat of solution	
	For 1 gram-mol.	For 1 gram
NH_3	8,430 cals.	496 cals.
SO_2	7,700	120
Cl_2	4,870	69
CO_2	5,880	134
H_2S	4,560	134
HCl	17,315	475

When hydrogen dissolves in water, heat to the amount of about 800 cals. per gram of the gas is evolved.[1]

In this whole problem it must be remembered that hydrogen forms a relatively large part of juvenile gas-mixtures. This gas has the highest specific heat of all substances yet measured, and its heat of solution in water is also very high. Its efficiency in melting a volcanic plug may perhaps be greater than that of the other gases and vapors put together.

In view of all the conditions, it seems correct to hold that the accumulation of gas beneath a solid volcanic plug develops a special kind of local furnace. The energy here transformed into heat is both potential and mechanical. In part, it is heat of solution; in large part, it may be due to chemical reactions; in part, it is due to the condensation of free gas constantly increasing in mass, within a closed chamber. The increase in mass is assumed to be due to the exclusion of gas in the crystallization at the walls of the abyssal injection, to diffusion from great depth, and perhaps to other molecular transformations within the magma chamber.

If the lava column is not kept supported, but withdraws for a time from the plug, the compression-melting of the plug must await sufficient accumulation of gas from beneath or the return of the fluid lava (because of general strains in the earth's crust or for other reasons) into the conduit. The mechanism is, however, the same as in the case

[1] G. N. Lewis, verbal communication.

just discussed, and the base of the plug is gradually melted. Piecemeal destruction of the base of the plug would also be brought about through overhead stoping by the lava column—a process evidently facilitated by just such surgings of the column as are characteristic of Kilauea and other volcanoes.

The re-fused magma must become gradually more and more charged with gas. How much gas per unit weight of rock would be required to fuse an average plug is obviously now impossible to declare, but the maximum quantity of gas in solution may not need to be more than 2 or 3 per cent. of the total weight of the magma in the actual conduit. The astounding explosive energy of newly awakened volcanoes, as shown in the vast heights to which fine ejecta are thrown and by the excessive comminution of the respective plugs, seem to indicate concentration of the gas to an even higher degree. The "evisceration" of some cones has possibly been due to the concentration of juvenile gases beneath plugs not yet sufficiently fluxed to permit of a reopening of the former vents by more moderate explosions. In neither case, however, is it probable that pure explosion could restore activity to the dormant volcanoes. Here again, as in the continuance of activity after the vent is opened, the problem is one of heat supply.

Another cause for dormancy is to be found in the sudden emptying of a lava-filled conduit by escape through a lateral fissure, forming satellitic intrusion, or distant surface flow, or both at once. This is a common event at both Kilauea and Mauna Loa. A multiple effect is produced. A large volume of specially concentrated juvenile gas is taken out of the vent, just so far diminishing the motive power and heat supply in that vent. As observed at Kilauea, the level of the conduit lava may not be restored to its former height for months or years. During that time the upper part of the conduit wall is cooling, and, through decrepitation and initial weakness, large masses fall from the wall and choke the vent. A resumption of activity at the surface must be delayed by these processes.

In the present argument we need not dwell on the fact that, if the volcanic mechanism is nicely balanced, a minute effect, like tidal strain, may pull the trigger and renew activity, for which the essential conditions have been long preparing. However, it seems clear that cosmical stresses do not seriously deform an abyssal injection during its lifetime as the feeder of a central vent. During such a period, which may be thousands of years in length but seldom or never millions of years in length, crustal readjustments must be minute, for even the greatest lava flows that could have been thus squeezed out at central vents are always very small in relative measure. The last-mentioned fact and the persistent recurrence of eruption at the main vent appear to forbid the hypothesis that renewal of activity at central vents is due to *renewal* of injection along new abyssal fissures. It would be highly improbable that the vent of a second injection would coincide with that of the first injection; and on the other hand, the great crustal disturbance accompanying the second injection should normally cause first-class lava floods at the initial vent, instead of the comparatively insignificant flows actually observed at central vents. Difficult as the problem is, the change from dormancy to activity does not, in general, seem to call for anything so drastic as a strong deformation of the earth's crust in its entire thickness.

In conclusion, the gas-fluxing hypothesis appears to be worthy of a leading place among those which can be constructed to account for the stubborn persistence in the revival of activity at a vent like Mokuaweoweo, Vesuvius, or Etna.

Small Size of Central Vents

The gas-fluxing hypothesis accounts for other general features of central eruptions. The small cross-sections of the vents at Kilauea, Hualalai, Mauna Loa, and even at Mokuaweoweo, as everywhere else in the world, are all of the order of size expected if the fluidity of each lava column is due to the slow passage of relatively minute masses of gas through those vents.

The writer is not able to agree with J. D. Dana, that the conduits beneath Kilauea and Mauna Loa are nearly equivalent in horizontal section to the great sinks ("calderas") in which the lava lakes are situated. Each of those sinks measures roughly 5 kilometers by 3 kilometers. The periodic rise and fall of the floor of the Kilauean sink (the only one carefully studied) can be explained on the assumption that its conduit has a much smaller cross-section. The "New Lake," after five years of activity, was emptied in 1886, and was proved to have had a depth of only a few meters. It was a saucer-shaped sheet of lava resting on solid rock. When the present Halemaumau is emptied, the lava runs out through a very narrow hole apparently less than 30 meters wide, and leaves a broad, funnel-shaped cavity. The action is like that of water running out of a domestic sink with centrally placed discharge; in both cases vortical motion is observed in the rapidly escaping liquid.[1] Similarly, the vast Kilauean lake of 1820 to 1860 is best interpreted as a true lake with solid floor, except for the narrow pipe which has always supplied the heat at this volcano. That pipe is probably the same pipe into which Halemaumau at times discharges its lava and from which the gas issues, to make the foun-

[1] C. H. Hitchcock, Hawaii and its Volcanoes, Honolulu, 1909, p. 254.

tains of "Old Faithful." All the Kilauean lakes have represented *overflows* from that vent or from a few, more temporary, narrow pipes. The fluidity of the lake has, in each case, been preserved for years by the process above outlined for the existing lake.

Whatever adverse criticism of this conclusion regarding Kilauea may succeed, it is certain that the whole area of either of the Hawaiian sinks cannot be directly taken to represent the size of the conduits. The surface areas of other lava columns active in historic time are all

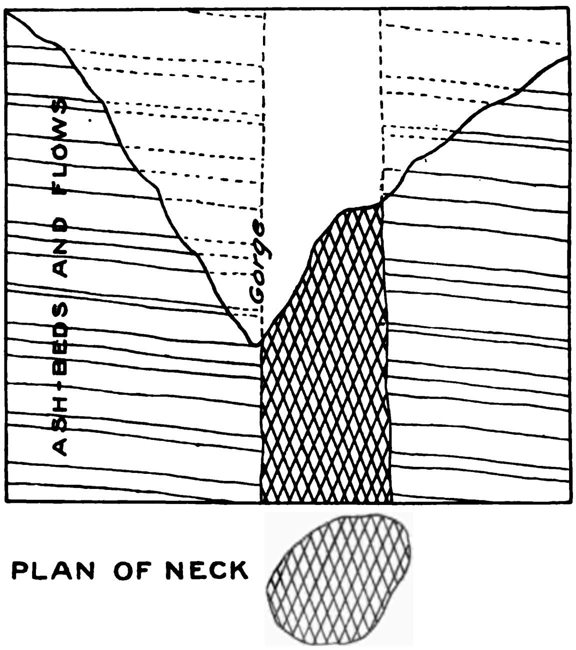

FIG. 136.—Section and plan of basalt-lava neck in a lateral gorge of the Iao valley in West Maui, illustrating the cylindrical form due to gas-fluxing. This was one of the subsidiary vents on the flanks of the great West Maui cone. There is no trace of faulting in the well-exposed ash-and-flow series and it is possible that this neck represents the local enlargement (by gas-fluxing) of one of the dike fissures now visible in the canyon. Nearly natural scale; major diameter of the neck about 50 meters. Sketched in the field by the author.

very much smaller. It is doubtful that any one of them, just below the floor of the flaring crater, has been as much as 1 kilometer. J. D. Dana computed the volume of the 1852 floor from Mauna Loa, which appears to have emptied the conduit to a depth of 2500 feet, as estimated from the difference of level of the summit lake and of the point of discharge. The result was 10,560,000,000 cubic feet.[1] This

[1] J. D. Dana, Characteristics of Volcanoes, New York, 1891, p. 240.

corresponds to the volume in a cylindrical conduit about 2300 feet or 700 meters in diameter. Similar calculations from other lateral outflows seem to give a mean diameter for the conduit of the same order of magnitude. Such a lateral fissure once opened, it would seem highly probable that the conduit would be emptied almost entirely by the simple outflow of the lava through the fissure; discharge into "subterranean cavities," would be unlikely. Moreover, it is possible that some of the 1852 lava represents a temporary rise of magma in the conduit, so that only part of the estimated volume of the flow can be used in calculating the average diameter of the Mauna Loa conduit. Thus, the calculation made according to the method outlined, strengthens the suspicion that the lava column of the world's vastest volcano is but a comparatively narrow pipe, perhaps much less than 600 meters in average diameter.

All of the ancient central vents now exposed as "necks" after prolonged denudation, are relatively small. (Compare Fig. 136 and also page 127 ff). The average diameter of the pipes recorded in geological literature is well under 300 meters.

We may conclude that the conduits of central eruptions are always small and of the order of magnitude appropriate to the gas-fluxing hypothesis. On any other hypothesis it is hard to explain the fact that the pipes of moderately large cones are about as large as those of the very greatest cones. In all cases there seems to be a *limital size* and that is controlled by the available heat supply along the axis of the vent. The size is small because the (indirect) fusing power of emanating gas must be strictly limited. Moreover, the cylindrical shape of each typical pipe is a solutional or fluxing form (Fig. 136).

Explosive Types: Magmatic and Phreatic

The foregoing genetic statement for the Hawaiian vents has been sketched in terms of a quite general process and it is necessary to glance at the relation of the hypothesis to the explosive type of central eruption.

Volatile matter occurring in the rocks of the contact-shell about any intrusive magma must show increased tension. If the intrusion is large and near enough to the earth's surface, this tension may lead to explosion in the roof of the igneous body. In case no incandescent matter is extruded, the explosion is not strictly volcanic. Following Suess, it may be called *phreatic*. A similar explosion may happen as a result of the slow conduction of heat from the conduit of a long dormant volcanic cone. Such a cone is normally porous. Rain-water, snow-water, or sea-water is trapped in the vesicular flows and loose tuffs, as these are in turn buried during the original growth of the cone.

The circulation of vadose water is also facilitated by this special porosity.

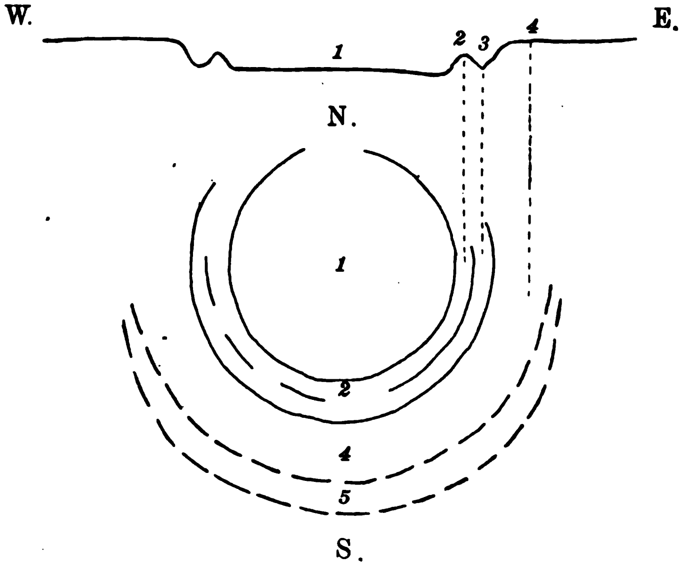

FIG. 137.—Schematic plan and section of the Rieskessel, with its zones of fracture (faults). (After W. Branco and E. Fraas, Abhand. k. preuss. Akad. Wiss., 1901, p. 39.) The flat floor of the depression is about 10 miles (16 km.) in diameter.

The suggestion of Suess that the remarkable explosion at the well-known Rieskessel was of phreatic origin has been supported by the

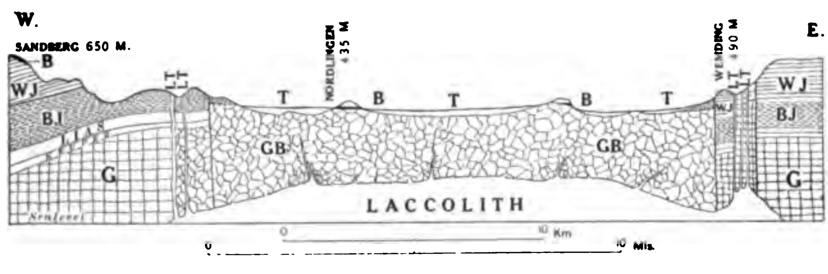

Fig. 138.—Section of the Rieskessel, showing inferred laccolith beneath. (Adapted from W. Branco and E. Fraas, Taf. 1 in ref. of Fig. 137.) *G*, Grundgebirge; *GB*, brecciated granite of the Grundgebirge; *BJ*, Brown Jura; *WJ*, White Jura; *B*, breccia; *T*, Tertiary and Quaternary sediments; *LT*, liparite tuff (dikes).

detailed studies of Branco and others.[1] Purely geological studies had indicated the presence of a large laccolithic mass beneath the great

[1] W. Branco, Abhand. kön. preuss. Akad. Wiss. Berlin, 1902, p. 14.

Ries depression (Figs. 137 and 138). That conclusion has been brilliantly supported by the magnetic studies of Haussmann in the region. The local disturbances of the needle in dip and azimuth can be explained, according to Haussmann, only by the assumption of one or more large subterranean bodies of basic rock (Fig 139).[1] In the Rieskessel itself the upper surface of the basic rock is calculated to be no more than 2 kilometers deep. Outside the depression, its average depth was estimated at 5 kilometers. Since the visible floor of the Ries is the granite of the "Grundgebirge," the basic mass or masses can only be interpreted as due to injection. Branco dates

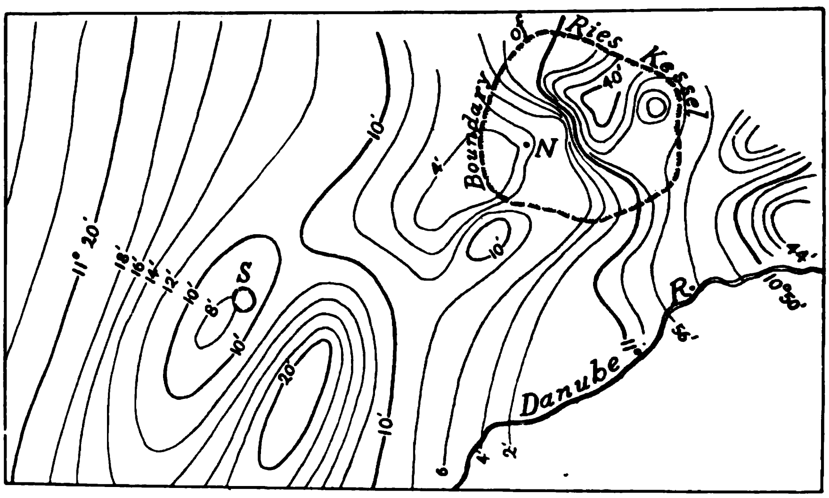

FIG. 139.—Magnetic isogones for 1901, Ries district, Germany. (After K. Haussmann, Abhand. k. preuss. Akad. Wiss., Phys.-math. Cl., 1904.) *N*, Nördlingen; *S*, Steinheim basin. The magnetic abnormalities are explained by postulating one or more large femic laccoliths not far from the surface. Scale, 1:880,000.

the intrusion of the Ries "laccolith" in the mid-Miocene. The overlying granite and its Mesozoic sedimentary veneer were domed by the injection and the top of the dome was largely destroyed by a phreatic explosion. It was followed by the appearance of a little liparitic tuff erupted at a few points in the newly formed basin, but the explosion itself was non-volcanic.

Branco and Fraas have concluded that the Steinheim basin is a small-scale equivalent of the Rieskessel, again showing the following succession of events: laccolithic doming, phreatic explosion, and sub-

[1] K. Haussmann, Abhand. kön. preuss. Akad. Wiss. Berlin, 1904, p. 137. Sauer has suggested that the liparite of the Kieskessel tuffs is due to the melting of the intruded granite by the basic magma. See W. Branco and E. Fraas, Abhand. kön. preuss. Akad. Wiss. Berlin, 1901, p. 54.

sidence on peripheral faults. No magmatic material was here erupted.[1] (Fig. 140).

According to Sekiya and Kikuchi, the great explosion of 1888 at Bandai-San was absolutely unaccompanied by the extrusion of lava.[2] A priest living on the mountain survived the explosion. He reported the vapors surrounding him to have been respirable, and the Japanese geologists conclude from all available data that the catastrophe was a steam explosion. There were no signs that juvenile gases formed an important part of the volatile mixture. This "eruption" of Bandai-San seems, therefore, to be an excellent example of a phreatic explosion *on* a true volcanic cone (Fig. 141).

Phreatic eruption means steam-explosion without magmatic extrusion. Kilauea represents magmatic extrusion without steam-explo-

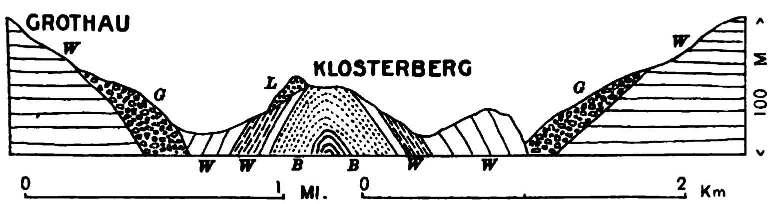

FIG. 140.—Section of the cryptovolcanic dome of the Steinheim Basin, Germany. (After W, Branco and E. Fraas, Abhand. k. preuss. Akad. Wiss., 1905, p. 21.) *B*, Brown Jura; *W*, White Jura; *G*, Gries formation; *L*, calcareous sinter. The doming is explained by laccolithic intrusion; the depression formed by phreatic explosion followed by erosion.

sion. Between these two extremes of terrestrial activity stands the type representing the vast majority of active and extinct central eruptions. In the non-volcanic or pseudo-volcanic activity of Bandai-San in 1888, as in a Kilauea or a Vesuvius, true igneous injection is a prerequisite. The gases given off at Kilauea form a nearly pure juvenile mixture with characteristic high temperature. The gases given off at Vesuvius form a mixture of juvenile, resurgent, and vadose volatile matter. A type of the resurgent gas is the carbon dioxide set free in the demonstrable assimilation of Mesozoic limestone and dolomite in the Vesuvian lava column. The gas and vapor given off at Bandai-San in 1888 was apparently almost purely vadose or meteoric in origin.

True volcanoes of the central-eruption type must vary enormously in the relative and absolute proportions of juvenile, resurgent, and vadose fluids composing their emanations. As the resurgent and

[1] W. Branco and E. Fraas, Abhand. preuss. Akad. Wiss., 1905, p. 21.

[2] S. Sekiya and J. Kikuchi, Jour. Coll. Science, Tokio, Vol. 3, 1889, p. 106. W. T. Lee (Bull. Geol. Soc. America, Vol. 18, 1907, p. 218) explains the Kilburn crater in New Mexico as being of phreatic origin.

vadose fluids are volatilized, heat is lost and the viscosity of the lava column rises. Assimilation of foreign rock in depth must lower the temperature, and in the end, increase the viscosity and also the average violence of explosions. In addition, magmatic differentiation generally brings the more silicious and more viscous pole to the upper part of the lava column, and aids in the preparation of explosive conditions.

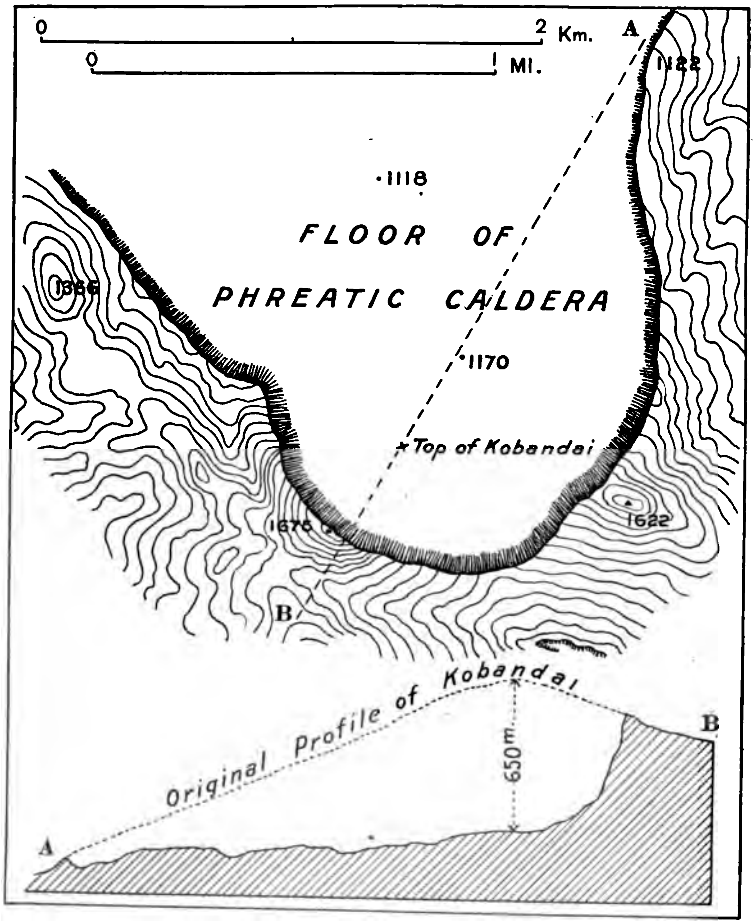

FIG. 141.—Plan and section of the caldera formed phreatically at Bandai-San (Kobandai), Japan, in 1888; after S. Sekiya and Y. Kikuchi, Jour. Coll. Sci. Japan, Vol. 3, 1889, Pl. 23. Heights in meters.

For these and other reasons, volcanoes of the central-eruption type have always had a great variety in dynamic habit and in the character of their ejectamenta. Yet, in every one of them, the essential problem is the same; it refers to the mechanism by which heat is kept supplied to the narrow, thread-like vents for long periods. To that problem, the questions as to how sea-water or vadose water is absorbed by underground magma, as to the dominance or subdominance of steam-explosion at individual vents, and as to the physical differences in the emanating lavas, are subsidiary. The problem of the Hawaiian vents is, from this point of view, the problem of all vulcanism reduced to its lowest terms. Here the gas-fluxing hypothesis seems satisfactory. In most other volcanic regions, where thick sediments are cut by the feeding magma or where heavy snows or rains wet the cones and, through seepage, cause steam-explosions, the control by juvenile gas may be obscured to the eye of the observer, but it still remains in every case the true cause of continued activity. Kilauea and Mokuaweoweo, like Matavanu and the vents in Réunion, teach us that steam-explosion is an adventitious feature of vulcanism. Except abyssal injection itself, the only indispensable process in central vents is *quiet exhalation.* Neither explosive drilling of the vent, nor ejection of lava, nor the contacting of meteoric or marine water with hot lava is indispensable. Each of these three processes is an expected effect of the slow emanation of juvenile gas from main abyssal injections or from their satellitic offshoots.

Magmatic Differentiation at Central Vents

The chemical variation exhibited in the lavas or pyroclastic materials successively ejected at the normal vent offers a problem of special importance. Volume for volume, this variability is much more striking than it is in the average large intrusive body—stock, batholith, laccolith, or sheet. At present many petrologists favor the pure-differentiation theory, which regards the splitting magma as primary and finds no place for notable assimilation of wall rocks by the primary magma. The writer believes that this question can only be cleared up by an attentive study of the world's plutonic masses, and that, in the nature of the case, its answer is not to be found at central vents. Field and chemical relations point indubitably to the fact that wholesale assimilation has occurred in the subjacent bodies classed as stocks and batholiths. Because of assimilation these masses generally have not the basaltic composition of the primary abyssal injection. The visible granite, diorite, or syenite represents the frozen top of an abyssal injection which is there a more or less differentiated syntectic. The lower part of each injection, approaching the substratum level, is probably basaltic and little modified in composition from its original condition. The syntectic-differentiation theory is so strong that the writer is disposed to prophesy its ultimate victory in the competition among explanations of the igneous magmas and rocks.

Since the lava column of every volcanic vent is an offshoot from an abyssal injection, the lava may represent either the primary basalt, or one of its differentiates, or syntectic material, or a differentiate from syntectic material. The rapid chemical variations in the extrusive magma at the average central vent shows that the conditions are here specially favorable for differentiation. Two of these conditions are implied in the essential mechanism of central eruption. The upward passage of juvenile and resurgent gases in great relative abundance lowers the "point" of solidification of the magma, increases the fluidity, and probably in still other ways aids in magmatic splitting. Secondly, the alternation of active and dormant periods means that the top of the lava column passes repeatedly through the narrow range of temperature (just above the crystallization point), where differentiation is most likely to take place.[1] High superheat is opposed to magmatic splitting.

Each of these conditions affects only a small volume of magma at any one time; if lava representing either pole of the differentiation is alone extruded, the volume of that flow must be relatively small. New magma rises in the vent. It may be mixed with that representing the other pole of the differentiation just accomplished. The mixture may be extruded, or it may itself be differentiated before the next outflow. Through absorption of foreign rock the new lava may have a composition unlike that originally differentiated.

It seems inevitable, therefore, that, at the restless volcanic vent, the ever-changing conditions must make a cone which is chemically heterogeneous to an extent not matched in the usual plutonic mass. Standard examples have been described at Electric Peak and Sepulchre Mountain in the Yellowstone Park; at the Lipari Island vents; at Tonopah, Nevada; at the Kaiserstuhl in Baden, etc.

Progress in Explosiveness at the Greater Vents

The explosive effect at central vents is a function of the magmatic viscosity and of gas-tension, which means gas-concentration.

Though the presence of much gas tends to lower the viscosity, temperature is obviously in dominant control over that property of magma. The initial store of heat in the abyssal injection is normally lost through radiation in the crater, through conduction at the roof and walls of the whole magma chamber, through assimilation of country rock, and possibly through the absorption of vadose water. As the whole mass cools, the juvenile gas emanates with ever lowering

[1] Injected masses normally pass through this temperature range only once before solidification.

temperature and the lava of the volcanic conduit must have a slow decrease of average temperature.

Magmatic differentiation must tend to affect the viscosity of the upper zone of lava, the exploding zone, in the same sense. The more acid differentiate usually rises toward the top of the vent. Though differentiation may be roughly cyclical, the successive splittings tend to make a secular increase of acidity in the upper zone of the conduit magma. Hence, irrespective of temperature, there is an increase of viscosity in the magma zone where explosions originate. The case of Mauna Kea, a basaltic lava-dome capped by cinder cones of andesite and trachydolerite, is an example of the partial control by magmatic differentiation over explosiveness. As the viscosity rises, the escape of magmatic gases is more difficult; the resulting tension is periodically relieved by explosions. Here also the action is cyclical, but there is, on the average, a slow increase in the amount of gas trapped before each explosion.

Again, the amount of volatile matter entering the magma column, either through assimilation of sediments or through the direct absorption of meteoric water, tends to increase with process of time. And, with the growth of a great, generally porous cone, the chance for phreatic explosion at or near the crater is favored.

All of these factors *work together* to produce maximum explosiveness at central vents which are long-lived because fed from great abyssal injections. The maximum normally appears in an advanced stage in the evolution of a first-class volcanic cone, though necessarily some time before complete extinction. Short-lived vents, opened above satellitic and therefore relatively small injections, will, of course, have no such tendency to great systematic change in explosiveness.

Lava Outflow at Central Vents

A noteworthy feature of all central eruptions is the relatively insignificant size of their individual lava flows. Thoroddsen has estimated the volume of the celebrated fissure eruption of Skaptar Jökull in Iceland at 12,320 millions of cubic meters. He gives the volume of one prehistoric flow as 43,160 millions of cubic meters; of a second, 23,250 millions of cubic meters. In striking contrast are the following examples of the larger recorded flows at volcanic cones. (See p. 290.)

Geological investigation shows that the flows from the central vents of Paleozoic and later periods have been of the same order of magnitude as the flows of the human period. With very few exceptions or none at all, these larger flows have issued from lateral fissures in the cones, and a large part of the volume of each flow is readily explained as the lava drained out, hydrostatically, from the upper part of each conduit. Without recorded exception all overflows at the main craters are incomparably smaller than those noted in the following table. Therefore, the ascensive force in central conduits is either slight, or, if powerful, is applied for short periods.

Locality of flow	Date	Volume in millions of cubic meters	Authority
Semeroe, Java	1885	300	De Lapparent.
Etna	1669	980	von Waltershausen.
Etna	1852	420	von Waltershausen
Etna	1865	92	von Waltershausen.
Etna	1879	57	von Waltershausen.
Mauna Loa, Hawaii	1852	299	J. D. Dana.
Mauna Loa, Hawaii	1855	455	C. H. Hitchcock.
Mauna Loa, Hawaii	1880–1	413	C. H. Hitchcock.
Mauna Loa, Hawaii	1907	153	E. D. Baldwin.

As above noted, the smallness of individual overflows suggests that the magma chambers which continue to feed central vents are very seldom deformed by important movements of the earth's crust. If the magma in the chamber were diastrophically pinched, we should expect, at times, relatively enormous lava-floods from central vents. Some authors hold, on the contrary, that the growth of a great cone sometimes occasions subsidence, so that crustal movement may be a consequence rather than a direct cause of lava overflow at central vents.

Without entering further into this subject, it will here suffice to mention the principal causes for lava outflow as deduced from the abyssal-injection premise. They are:

1. Very minute deformation of the feeding magma chamber.
2. The effervescence of lava, due to the periodic accumulation of magmatic gases in the vent. These gases may be juvenile or resurgent.
3. The assimilation of country rock in depth, leading, probably, to increase of volume.
4. The increase of volume through heating in the conduit "furnace" —a process specially likely to occur during the dormant period when the vent is temporarily plugged.

These causes may co-operate, but at basaltic volcanoes the third is clearly subordinate.

The Two Types of Lava Flows

A preliminary study of the Hawaiian lavas, with respect to their field habit, has led the writer to suspect significant gas-control even in this detail of vulcanism. On the average the vesiculation of pahoehoe or ropy lava was found to be more evenly developed than in the aa or block lava. The rather uniformly disseminated vesicles of pahoehoe are of relatively small and relatively uniform size, and tend to have spherical form. The irregularly distributed vesicles of aa lava are generally larger, though more variable in size; much fewer in number, and of less total volume per unit volume of rock; and more irregular in shape. These facts indicate a more uniform distribution of gas in the pahoehoe than in the aa type. The aa vesicle, which is often thousands of time bigger than the average pahoehoe vesicle, has undoubtedly grown through the coalescence of many bubbles of gas. Such growth must in very high degree (see page 262) favor the escape of the gas into the air, and we may regard these large vesicles as representing so much gas trapped in the freezing lava. Before solidification had set in, gas must have escaped from every aa flow in large volume. In fact, observers of the two types in actual movement agree that the gas emanation from flowing aa lava is much more abundant than that from flowing pahoehoe.[1]

The difference of field habit in fluent lava and block lava is thus explained, with some show of probability, by the relative abundance of volatile matter and, still more, by the evenness of its distribution. For both reasons pahoehoe lava is certain to be less viscous than is aa lava, other conditions being the same; the pahoehoe moves, as it were, on molecular and vesicular "ball-bearings."

The fact that many flows, from the very points of emission, are altogether of the one type, while others are throughout of the other type, shows that the differences of gas-distribution are developed in the vent. The problem as to exactly what circumstances there control the gas-distribution has not yet been solved. Slight differences in temperature, or differences in the advance toward solidification (with gas expulsion) may be the effective cause. The writer has observed a tendency for the phenocrysts of aa lava to be of larger average size than those in pahoehoe lava which gives practically the same oxide proportions in ordinary chemical analysis (volatile matter other than water neglected); but he is as yet not prepared to regard this as an established rule.

Vulcanism Originating in Satellitic Injections

We have so far considered central vents as, in general, direct offshoots of main abyssal injections. The latter have been described:

[1] Cf. J. D. Dana, Characteristics of Volcanoes, New York, 1891, p. 242. Judge Hitchcock describes a typical Hawaiian aa flow as advancing "with no explosions, but a tremendous roaring, like ten thousand blast-furnaces all at work at once."

as dike-like, though often of great widths; as extending upward from the primary substratum, nearly or quite to the earth's surface for some such vertical distance as 40 kilometers. Batholiths have been interpreted as chemically modified abyssal injections of the primary basalt. Plutonic stocks and bosses represent cupolas in batholithic roofs. Stocks, bosses, and batholiths compose the group of "subjacent" intrusive bodies. Laccoliths, sheets, and ordinary dikes are individualized bodies, satellitic with respect to their feeding abyssal injections and, like the latter, owe their intrusion to a simple parting of the invaded rock-formations. Irregular bodies intruded in the same fashion have been called "chonoliths"; they form a fourth class of "satellitic injections."

All satellitic injections soon lose thermal and hydrostatic connection with their respective abyssal injections. All laccoliths and chonoliths, like most sheets and some dikes, have solid floors during most of their magmatic activity. If a satellitic injection is of large size, its content of heat energy and of gas may suffice to open one or more vents to the earth's surface, according to the methods already described. Volcanic action is thus initiated which differs in some respects from that due to direct emanations from a main abyssal injection.

The importance of this fact is manifold. Its recognition aids in our understanding: the short life of many volcanoes of the central type; the lack of lava flows at many of them; the independent activity of neighboring vents; the chemical dissimilarity of the lavas from neighboring vents; the quite common clustering of many small vents in a region which shows no trace, or but few traces, of the alignment of its volcanoes; and the frequent evidence of surface deformation in such regions. The evidences for this type of vulcanism are indirect, but they are numerous; taken together, they form a combination of no mean strength.

In the first place, an excellent analogy to the vents from satellitic injections can be observed in nature. The blow-holes and driblet cones formed on the surface of the deep lava flows of Etna, Réunion, Hawaii, Savaii, etc., are continued in their brief activity because of the thermo-gaseous energy of lava quite removed from the parent vent. The blow-holes occasionally opened in the dome-shaped "bulges" or "tumuli" formed on the pahoehoe of Hawaii or Réunion are particularly instructive, for such tumuli, when just formed, represent small laccoliths of still fluid lava capped by recently frozen lava-crust.

To the weight of analogy is to be added that of *a priori* reasoning. According to almost any of the extant theories of igneous action, vulcanism originating in magmatic satellites should be *expected*. Many satellitic injections of great size have been exposed by erosion; it would

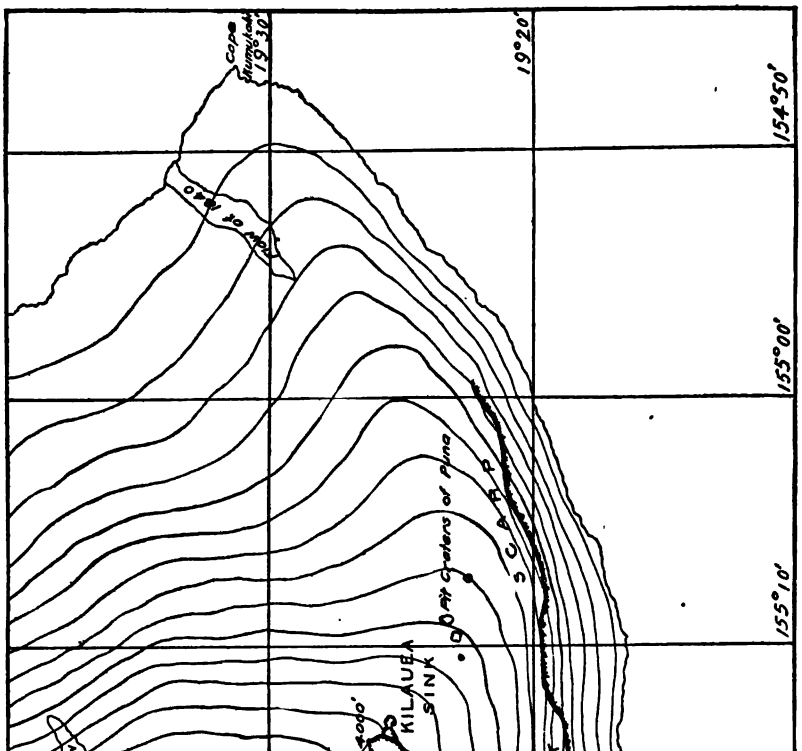

FIG. 142.—Part of the Government map of southeastern Hawaii, showing that Kilauea, like the Puna pit-craters, is a hole fluxed in a gently sloping plateau, and illustrating the hypothesis that Kilauea is kept active through the thermal activity of a large laccolith injected into the flank of Mauna Loa. Scale, 1:530,000; contours in feet.

be a matter for distinct surprise if none of them ever perforated its roof.

Field observation must naturally make the compelling test of the principle. Have we any active example? Can we find traces of it in denuded regions where erosion enables us to study the anatomy of volcanoes? Each method of applying the field test has its own difficulty. In the first case the satellitic injection is inaccessible and can only be located through inference; in the second case it is but rarely that denudation could expose the injected mass without destroying the conduit above. Yet the writer believes that the field inferences seem to support the principle.

The case of Kilauea as an illustration (Fig. 142) was detailed in the writer's original paper on "The Nature of Volcanic Action" (1911). Considering the field relations of the Hawaiian vents it seems justi-

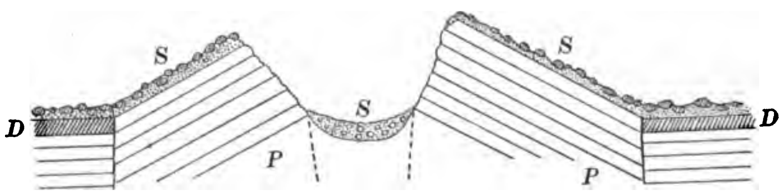

FIG. 143.—Section of the Hrossaborg volcano, Iceland. (After H. Reck, Monatsber. deut. geol. Ges., Vol. 62, 1910, p. 316.) *P*, palagonite; *D*, dolerite; *S*, sand and breccia. This is an Erhebungskrater, formed by explosion of gases emanating from an injected, laccolithic mass of lava, and thus illustrates "subordinate" volcanoes.

fiable to class Kilauea tentatively as the living vent of a still liquid satellitic injection. We may also conclude that it is unsafe to deny, simply because of the hydrostatic independence of the two active Hawaiian lava columns, that a primary fluid substratum of basaltic composition underlies the whole island.

An Icelandic Example.—Reck has suggested that the crater of the Hrossaborg in central Iceland is a gas-exploded opening (diatreme) in the roof of a laccolith. The injection is of comparatively late date, presumably Recent or Quaternary[1] (Fig. 143). A volcanic pipe at Oorlog's Poort, Cape Province, South Africa, is described as having been fed from a sill.[2]

We may now briefly note other probable examples of the opening of vents above satellitic injections.

Tertiary and Older Vents from Satellitic Injections. Swabian and Scottish Examples.—As a result of his extraordinarily thorough

[1] H. Reck, Monatschr. deut. geol. Ges. No. 4, 1910, p. 293.

[2] A. L. du Toit, 16th Ann. Rep. Geol. Comm., Cape of Good Hope, 1912, p. 123.

study of the mid-Miocene eruptions in Swabia, Branco concluded that the Urach region is underlain by a "kuchenförmige Masse," or laccolith. In ground-plan its estimated diameters range between 30 and 45 kilometers. Its position coincides with that of a very low, but broad

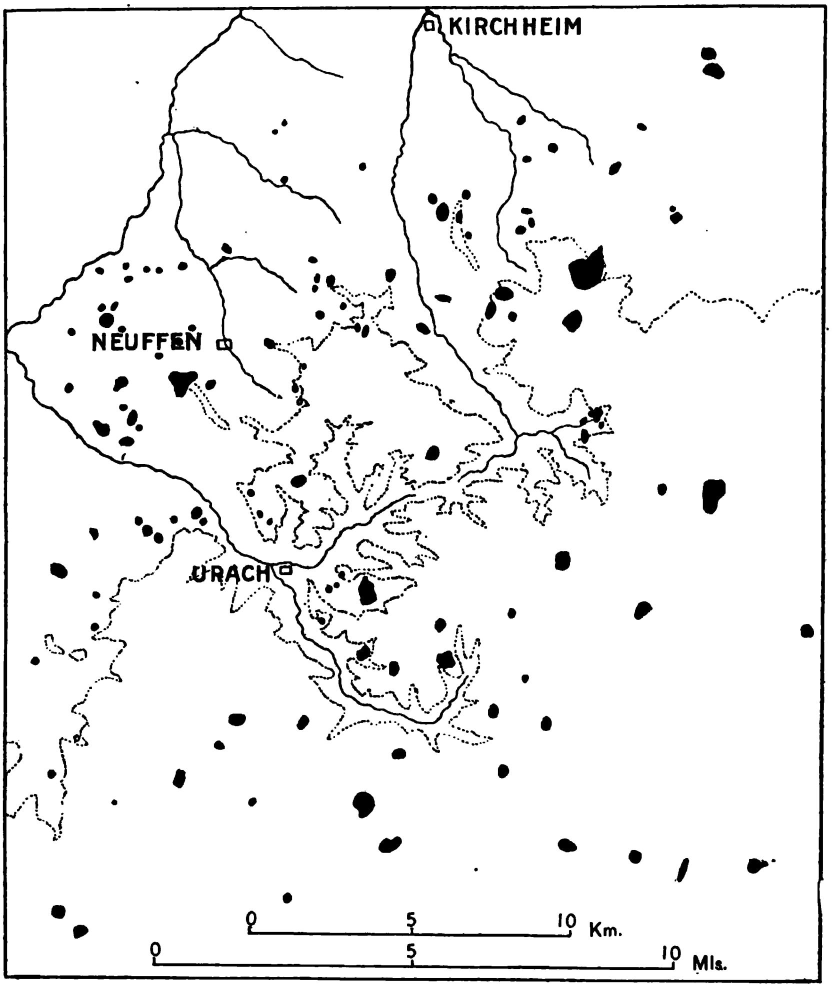

FIG. 144.—Map of part of Swabia, showing positions (black spots) of "Vulkan-Embryonen." (After W. Branco, Schwabens 125 Vulkan-Embryonen, 1894.) The dotted line is the edge of the Swabian Alb escarpment.

doming of the Jurassic strata in the Bavarian Alb, as determined by Regelmann. Through secular erosion, the frontal escarpment of the Alb has retreated at least 25 kilometers since the volcanic epoch (Fig. 144).

On the top of the Alb plateau are thirty-eight tuff vents; in the escarpment are thirty-five more, and in the "Vorland," or region traversed by the escarpment in its southward retreat, there are fifty-four tuff vents and five basaltic vents (Fig. 145). No lava flows occurred on the Alb, and the few lava necks have become visible because of denudation in the "Vorland." Though the explosion funnels are still more or less intact on the Alb, the largest of them, the Randeck "Maar," does not exceed 1 kilometer in diameter. The average diameter of the 132 vents is far less. The evidence is clear as to the short life of each of these vents, which Branco has made the world type of "volcanic embryos." Their brief, almost wholly explosive activities,

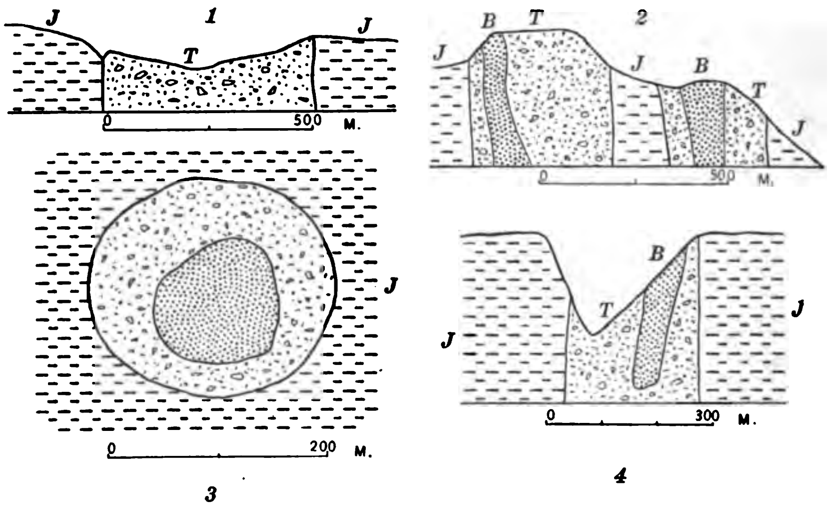

FIG. 145.—Plans and sections of Swabian necks ("Vulkan-Embryonen"). (Same ref. as for Fig. 144, pp. 202, 367, 376.) *1*, Neck south of Hengen. *2*, Necks at the Hohbohl and Gözenbrühl. *3*, Plan of the Gözenbrühl neck. *4*, Neck east of Seeburg. *J*, Jurassic strata; *T*, tuff; *B*, basalt.

their distribution in a cluster. without reference to master fractures, and the dome-like warping of the Jurassic beds in this region, all declare the justice of Branco's laccolithic hypothesis. Furthermore, his discussion of Mandelsloh's 340-meter boring at Neuffen shows that the temperature gradient in at least one part of the Urach region is abnormally high, about 10 meters per degree Centigrade. Branco regards the abnormal gradient as due to the wave of heat still being conducted from the mid-Miocene injection. This suggestion is by no means extreme and it clearly tends to support his laccolithic hypothesis.[1]

The peculiar abundance of small tuff-necks of Permian age in parts

[1] W. Branco, Schwaben's 125 Vulkan-Embryonen, Stuttgart, 1894. Cf. E. Suess, Das Antlitz der Erde, Bd. 3, 2te Hälfte, 1909, p. 655.

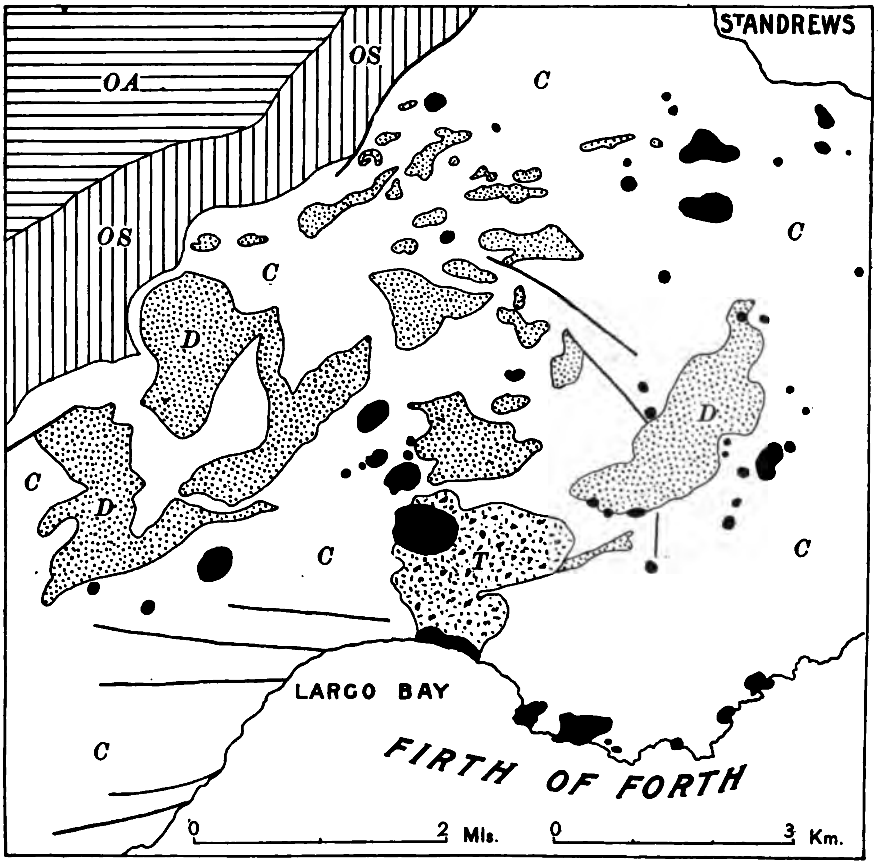

FIG. 146.—Map of part of Fifeshire, Scotland. (After A. Geikie, Geology of Eastern Fife, 1902, map.) *OA*, Old Red (andesite and dacite); *OS*, Old Red (sandstone); *C*, Carboniferous; *D*, dolerite sills; *T*, tuffs (Permian); *solid black*, necks (Permian). The close association of sills and necks suggests the possibility that the latter represent "subordinate" vulcanism.

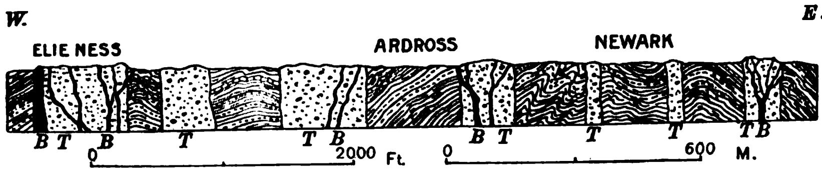

FIG. 147.—Section of the coast of Fifeshire, between St. Monans and Elie, showing volcanic necks in folded Carboniferous sediments. (Same ref. as for Fig. 146, p. 112.) *T*, Agglomerate and tuff; *B*, basalt. Scale approximate.

of Scotland is subject to a similar tentative explanation. Various memoirs of A. Geikie have made these vents famous as types of true necks. In Fifeshire, eighty of them have been counted in an area, measuring 18 kilometers by 10 kilometers (Fig. 146). In western Ayrshire, sixty vents are found in an area measuring 60 by 30 kilometers, and, of those vents, twenty are necks occurring within an area of 35 square kilometers. In the great majority of cases, Geikie and his collaborators have been unable to find any connection between the positions of the necks and lines of dislocation. The Carboniferous strata have suffered sieve-like perforation like that of the Juras-

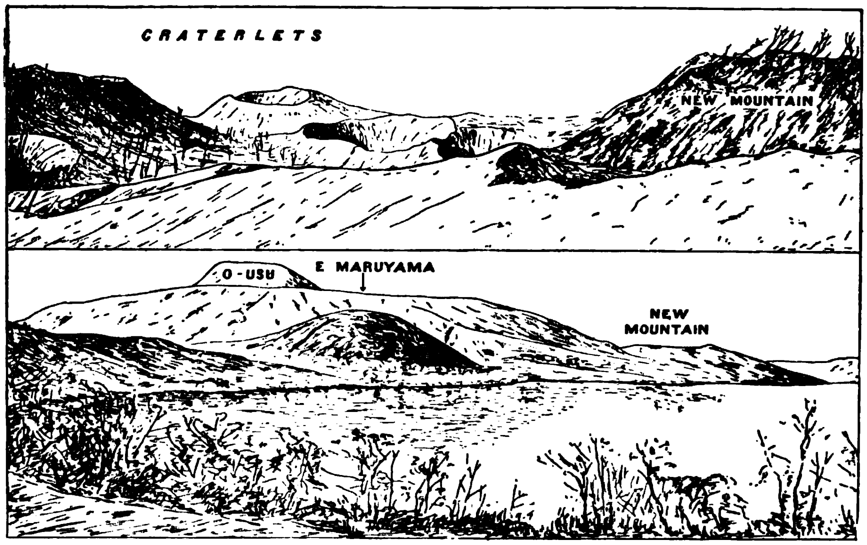

FIG. 148.—(1) Fault face of the New Mountain at Usu-san, Japan, with tilted trees on top; to the left, craterlets formed during the period of elevation. (After E. B. Bailey, Geol. Mag., Vol. 9, 1912, p. 248, and F. Omori, Bull. Imp. Earthquake Investigation Comm., Vol. 5, No. 1.)

(2) Usu-san with the New Mountain as seen from across the Lake of Toya. (Same ref.)

sic beds in Swabia (Fig. 147). In each of the Scottish districts, the lower part of the very thick Carboniferous sedimentary series carries numerous thick sills of dolerite. These sills are mapped as chiefly Carboniferous in date, but Geikie thinks that some of the Fifeshire sills at least are Permian. The steady association of tuff-neck and sill in the Scottish shires scarcely looks accidental.

Gas emanations from the magma forming these actual intrusives or similar ones occurring in the underlying pre-Carboniferous formations, together with the possible emanation of gas from the heated

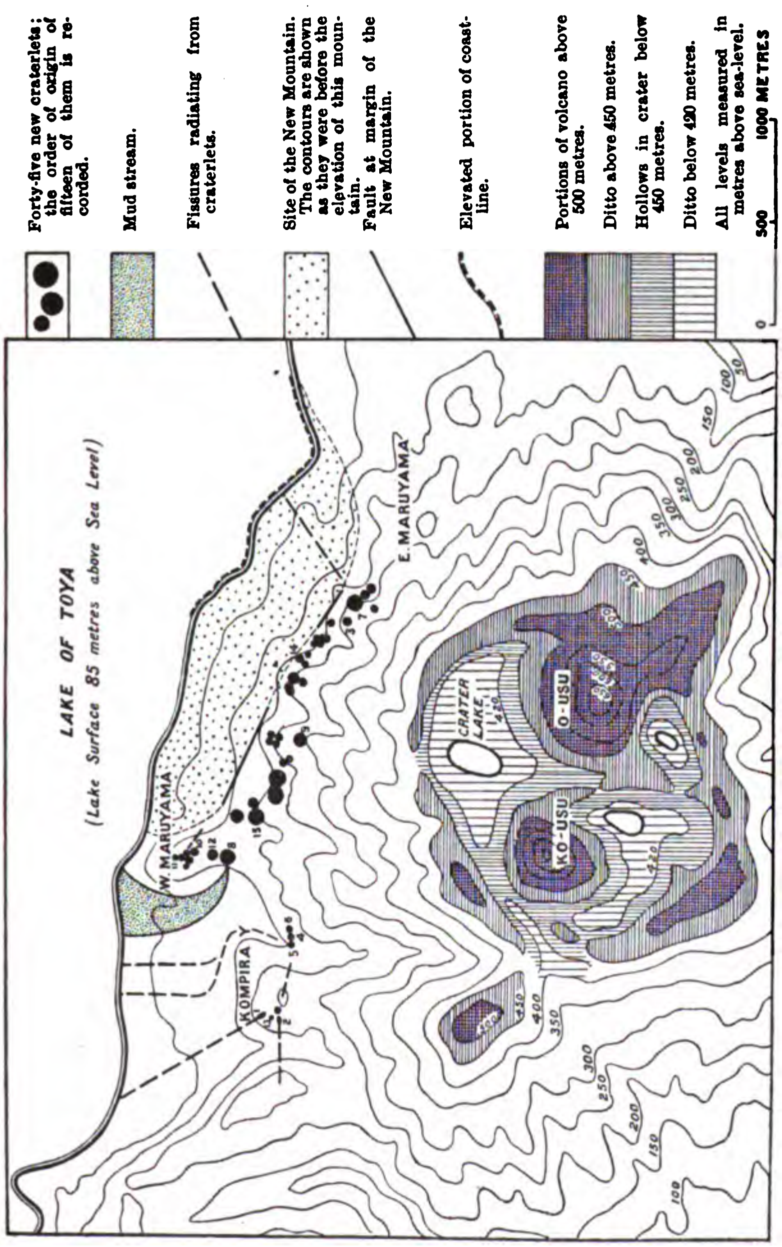

Fig. 148a.—Map of Usu-san, Japan. (Same ref. as for Fig. 148.)

country-rock, would seem to be competent to explain most of the tuff-necks. Explosive drilling (diatremes) and gas-fluxing might in turn dominate in the opening of the vents. The total activity must be small, because each gas-emitting or lava-emitting chamber was small.

The list of districts where the writer suspects secondary vulcanism includes also the area of necks in Noss Sound, Shetland.[1] These are small and the volcanic throats are filled with a coarse agglomerate of sandstone and shale. Peach and Horne infer that the vents never emitted any streams of lava.[2] The eruptivity is referred to the Lower Old Red Sandstone period. The date may be nearly the same as that of the injection or the thick sills and dikes which abound in the Noss Sound region.

Finally, the forty-five new craterlets ranging along the foot of the "New Mountain" at Usu-San, Japan, afford other probable examples (Figs. 148, 148*a*). This remarkable deformation of the land surface is clearly due to magmatic injection not far below, and it seems likely that the craterlets have been opened through the independent activity of the injected mass of magma.

A Necessary Division of Central Vents.—It is obviously difficult to devise field criteria which shall infallibly distinguish central eruptions respectively originating in main abyssal injections and in satellitic injections. Long and strong activity, large outflow of lava, and alignment in chains will generally characterize the central vents of abyssal injections. Brief activity, small output of lava, cluster grouping, and traces of surface deformation in the region are the generally expected features of the central vents of satellitic injections. As one or more of these features is absent or is obscured, the classification is hard to apply.

The chief object of the foregoing discussion has been, however, not to propose a division directly useful in field work, so much as to erect a fence over which speculation about the earth's interior cannot pass. The best way to check mischievous speculation is to advance beneficent speculation, founded on all the known facts. For example, the bold statement that there can be no magmatic substratum beneath a district bearing two simultaneously active lava columns of differing heights can no longer be made without an investigation of their nature as "principal" vents (abyssal injections) or "subordinate" vents (satellitic injections). The formal classification is of positive use in recognizing a mechanism by which the petrographic contrast of the

[1] A. Geikie, Quart. Jour. Geol. Soc. London. Presidential Address, Vol. 48, 1892, p. 95.

[2] B. N. Peach and J. Horne, Trans. Roy. Soc. Edinburgh, Vol. 32, 1884, p. 359, and Vol. 28, 1878, p. 418.

lavas from neighboring vents may have originated. If two of these are opened above different satellitic injections, the chances are good that the magmatic histories of the injections will be different; their emanating lavas would diverge in chemical type according to the progress respectively made in the formation of syntectic and differentiated magmas.

Some "subordinate" vents are monogenetic in Stübel's sense, and there are a few analogies between the system of vulcanism here suggested and that elaborated by the illustrious German. But the writer cannot agree with Stübel's principal conclusion as to the motor power in vulcanism, and entirely fails to find geologic or petrologic evidence for the existence of his "Panzerdecke."

General Summary

The general hypothesis briefly outlined assumes that the earth is exteriorly composed of successive shells of density increasing with depth. Beneath the interrupted sedimentary shell is a continuous solid "granitic" shell, and still deeper, an *eruptible basaltic shell or substratum.* All igneous action, since an early pre-Cambrian period, is the result of the mechanical intrusion of the substratum basalt into the overlying shell. This fundamental process is specifically called "*abyssal injection.*" It is not a hypothetical process, but one which is clearly apparent in the chemistry and field relations of igneous rocks. The conditions leading to abyssal injection form a subject of great theoretical difficulty, but the discovery of the exact mechanism is not essential to the presented explanation of volcanoes. Nor is it necessary to decide on the degree of viscosity characterizing the basaltic substratum, although it is pointed out, once again, that the observed small amount of deformation of this planet under cosmical stresses does not prove that the substratum is crystallized. The central thesis of this chapter is that all vulcanism is a consequence of abyssal injection, or in other words, that from the date of the oldest known pre-Cambrian lavas, every volcanic vent has been opened because of a preliminary *mechanical intrusion of molten basalt* into the *acid earth-shell.*

Emphasis is laid on the absolute necessity of classifying the gases and vapors which do important work at volcanic vents. These are either magmatic or phreatic in origin. The *magmatic* volatile fluids are subdivided into *juvenile* and "*resurgent*"; the *phreatic* fluids into *vadose* and *connate.* Each of these classes may be important in the dynamics of volcanic explosion; on the other hand, the juvenile magmatic gases are assuredly the most important in keeping a volcanic vent alive.

Central eruptions are of two main classes. In the "*principal*" class each vent represents emanations from a main abyssal injection; in the other, "*subordinate*," class each vent originates over a magmatic body (laccolith, sheet, etc.) which is satellitic with respect to a main abyssal injection. Of these two classes, "principal" volcanoes must, on the average, be the more intense in activity, of longer life, more productive of lava-flows, and more clearly related to crustal fissures. The facts of the field suggest that Kilauea is a "subordinate" volcano. Tertiary and Paleozoic examples are probably represented in Swabia and Scotland. The localization of central vents and their very common alignment are explained by the principle of abyssal injection. Lack of alignment in a group of vents is suggestive of their "subordinate" origin. In the nature of the case, "subordinate" vents must, in their activities, show a high degree of *independence* of one another and of neighboring "principal" vents.

Continued eruption at a central vent is a heat problem. The primary heat of its abyssal injection is not the only source of thermal supply. A leading place in the theory should be kept for the supply due to chemical reactions among the primary constituents of the injected magma. Abyssal injection means an enormous change in the pressure conditions of the magma. As a result, the juvenile gases rise toward the top of the magma chamber. They are concentrated in the actual volcanic pipe and, according to the law of mass-action, exothermic reactions on a large scale are to be expected. The possibility that energy was potentialized in the primitive basaltic substratum by the formation of dissolved endothermic compounds, like cyanogen, ozone, hydrogen peroxide, etc., is indicated. In consequence of changes in pressure and temperature, due to injection, the dissociation of those compounds and the formation of new, stable compounds formed partly or wholly from their elements, give a double source of heat in the magmatic column. The heats of formation for the probable reactions are so great that small masses of juvenile gas might furnish a relatively large supply of heat. Moreover, it seems likely that exothermic reactions occur when the liquid components of magma attain chemical equilibrium under the new conditions induced by the injection of an abyssal magmatic wedge. Though it is at present impossible to estimate the fraction of the total volcanic heat due to chemical reactions, a working philosophy of vulcanism should give due regard to the hypothesis that a central vent is a *true furnace*.

Using Siegl's recent results from experiments, the writer has calculated the approximate rate of heat loss through radiation at an active crater. The loss by radiation occurs, in general, at a much faster rate than the heat loss by conduction into the walls of the vent for a depth of many kilometers. The methods of the transfer of heat from the depths are discussed.

The principle of "*two-phase convection*" is concluded to be essential to the maintenance of prolonged activity at central vents. This conception is illustrated by the analogy of solid spheres moving, under gravity, in viscous fluids.

Explanation is offered for the dormancy and related periodicity of certain vents; for the typical shape of such a vent, and for its comparatively small size. These features, when coupled with long persistence in activity, are chiefly dependent on two-phase convection. Since the latter process is, in its turn, dependent on the rise of gases in the magma chamber, this general conception of central eruptions is called the *gas-fluxing hypothesis*.

The petrographic variety of lavas is to be largely explained on principles which have been demonstrated in plutonic geology. The lavas emitted at central vents may be: primary basalt; differentiates of pure primary basalt; syntectic magmas, *i.e.*, those produced by the solution of foreign rock in primary basalt; or differentiates of syntectic magmas. The petrographic diversity in the lavas of neighboring volcanoes becomes better understood through the recognition of the two ("principal" and "subordinate") classes of central vents.

The explosiveness of volcanoes is a necessary step in the march of events following abyssal injection. The inciting cause is to be sought in the tension of resurgent gas as well as of juvenile gas. Progress in magmatic differentiation tends to favor explosiveness to an important degree. Magmatic and phreatic explosions must be distinguished if the tangle of vulcanological facts is to be unravelled. Though the rise of hot magma into rocks charged with vadose or connate water does often cause explosion, the steam-pressure produced by such volatilized water can no more be regarded as the cause of vulcanism than is the boiling of a kettle the cause of the heat in the stove. The formation of the magma column, extending through the earth's "granitic" and sedimentary shells to the surface, is the crucial problem. It is obviously a mere matter of detail whether or not the country rocks at the upper end of the magmatic column are wet and therefore explosive.

The facts of volcanic geology seem, therefore, to co-operate with the facts of plutonic geology in showing that the essential process in igneous action on this planet is the rise of basaltic magma from the universal substratum along abyssal fissures in the earth's acid shell.

CHAPTER XIV

ECLECTIC THEORY OF THE IGNEOUS ROCKS

Summary of the Eclectic Theory

The genetic scheme outlined in the last five chapters is the result of an attempt to combine the soundest ideas of petrology in a general working theory. The value of the scheme cannot fully appear until it is applied in detail to the different rock clans and rock bodies of the world. Before entering on such concrete studies it will be expedient to summarize the proposed theory.

1. It is practically certain that the earth is stratified, at least roughly, *according to density*. This is the conclusion of cosmogonists, like Laplace, Legendre, Roche, and others; of mathematical physicists, like G. H. Darwin and Fisher; of seismologists, like Oldham; of geologists, like A. Geikie and many others. The deeper layers of the globe are not known ever to have furnished material for the visible bodies of igneous rocks.

2. To explain the igneous rocks it is only necessary to deal with three exterior earth-shells. The thin *sedimentary*, and the thicker *acid*, *crystalline* shell beneath are both visible in part and may be reasonably inferred to extend much more widely than their respective total outcrops. The sedimentary shell is known to be discontinuous; the underlying acid shell is known to form most of the area of each continental plateau, but it may not underlie all of each ocean basin. From the phenomena of igneous action the existence of a basic shell, still deeper, is inferred. It may be discontinuous; if so, its parts underlie every large area of the earth's surface, continental or oceanic. It may be solid, though preference is given to the view that it is fluid, perhaps a very rigid fluid. In either case it is known to be composed of eruptible matter. Many facts compel belief that this third shell is basaltic in composition. In accordance with the ascertained facts of petrology and geology, the *basaltic substratum* is held to be the only shell of the earth which, since an early pre-Cambrian period (typified in the Keewatin), has been hot enough for spontaneous eruption. Probable as this relation may be, it is to be clearly recognized as an assumption, the basal assumption of the whole theory to be outlined. Such is the writer's conception of the exterior shells of the earth, as deduced from the facts of modern geology. Such appears

to have been the general conception of von Cotta who generalized from the knowledge of the earth gained up to the year 1858.

3. It is known that the basaltic magma so abundantly erupted since the Keewatin period cannot be due to the liquefaction of either the sedimentary shell or the acid shell of the earth (together called the "crust"). Hence, basaltic eruption implies the injection of basaltic magma along *abyssal fissures* in the crust. Each abyssal fissure must usually grow narrower toward the top, and hence the primary basalt filling it is called an *abyssal magmatic wedge*. The mechanism of this injection can be discussed only hypothetically. The writer's general conception of it has been independently reached by Johnston-Lavis, and Fisher has deduced some of its essential elements.[1]

4. Abyssal injection involves the production of some superheat in the basalt raised to, or nearly to, the earth's surface. If the magmatic wedge is of large size, a limited amount of *marginal assimilation* of the wall rock is a necessary consequence of the injection. This deduction from observed fact agrees, in principle, with the views of many of the advocates of the hypothesis of marginal assimilation in depth, including von Cotta, de Beaumont, Fouqué, Michel Lévy, Lacroix, Barrois, Loewinson-Lessing, Brögger, Lawson, and many others.

5. The larger basaltic wedges perform *magmatic stoping* to a variable, but often great, extent. The process has been described by Goodchild, Lawson, Barrell, Ussing, and the writer. However, the four authors first mentioned do not associate the process with primary basalt.

6. Stoping involves *abyssal assimilation* of the country rocks. This consequence of stoping has been specially emphasized by the writer and (as a recent letter from Professor Cole shows) by Goodchild.

7. Both the primary basalt and each of its solutions with crust-rock is, under certain conditions, subject to *magmatic differentiation*. This principle is now accepted by practically all workers in modern petrology, though many of them deny the importance of syntectics and are content to regard almost all igneous rocks as derived from either primary magmas or from liquid differentiates of these.

8. The essential facts known concerning *batholiths*, *injected bodies*, and *volcanic vents* appear to find explanation on the hypothesis of the primary basaltic wedge. The batholith is here interpreted as an abyssal wedge or gigantic dike which has been physically enlarged and chemically modified at its summit.

The petrogenic scheme outlined is thus seen to be an *eclectic theory*. Not merely for the interest of an academic study pursued in the

[1] O. Fisher, Physics of the Earth's Crust, London, 2nd edition, 1891.

library, but because of the pressure of facts encountered in the field, the writer has "selected and appropriated" whatever seems best in all the earlier theories of the igneous rocks. He has found reason for believing in essential tenets of the French petrologists and in those of the German and other petrologists who refused to follow de Beaumont and his successors. Of late years the national boundaries, so curiously persistent between the opposing schools of petrogenic thought. have been breaking down. Michel Lévy and Lacroix have retained their belief in assimilation while learning to grant the great importance of differentiation. On the other hand, an increasing number of German, Austrian, Scandinavian, British, and American petrologists are leaving the extreme position of the pure differentiationists, so long led by Rosenbusch, Brögger, Teall, Iddings, Pirsson, Washington, and others. These tendencies of themselves suggest the justice of the eclectic position.

It is significant that some of those petrologists who still adhere to pure differentiation as the only important cause of the diversity of igneous rocks, have had comparatively little experience with igneous rocks *in the field*. On the other hand, steady contact of other workers with a succession of large igneous intrusions has often, if not generally, led them to see the necessity of large-scale assimilation. Among the writers of such ripe field experience are Barrois, Michel Lévy, Kjerulf, Sederholm, Högbom, E. C. Andrews, Emerson, Coleman, Lawson, Brock, Camsell, and many others.

The writer came to belief in assimilation as a petrogenic factor of first rank through two stages of reasoning. His early studies on the batholiths of the "porphyritic granite" of New Hampshire, on the stocks of Mount Ascutney, Vermont, and on the great batholith at Barre, Vermont, led him to conclude that at least some of the batholithic magmas had *incorporated* their country rocks. The absence of chemical "consanguinity" between magma and invaded formation in practically every case seemed, however, to forbid the notion that incorporation also meant solution of the country rock. The difficulty was removed through the development of the stoping hypothesis at Mount Ascutney. That hypothesis not only involved the necessity of abyssal assimilation; it also explained the general absence of "transgressive junctions" between batholith and wall-rock and accounted for the general failure of their chemical consanguinity. Incidentally, the development of that hypothesis, while involving the obvious principle of magmatic differentiation, also showed the fallacy of the prevailing arguments against marginal assimilation in plutonic magmas. Since publishing his first outline of the hypothesis, the writer has studied in greater or less detail more than two score of stocks and batholiths in British Columbia, Idaho, Montana, California, New England, and Eastern Canada. In every case the general field conditions affecting the hypothesis were found to be similar to those at Mount Ascutney and of the other localities where the results of actual field work had prompted this conception of intrusive mechanism. With the strengthening of its proofs the writer's belief in the great efficiency of assimilation has strengthened. He is not prepared to state the relative importance of the assimilation at main contacts as compared with that of stoped blocks in depth, although, as indicated in Chapter XI, the latter type has certain plutonic conditions in its special favor.

Loewinson-Lessing's General Theory

On referring to the literature of petrology, the writer found that Loewinson-Lessing had, on independent grounds, also arrived at an eclectic theory, embodying both doctrines of differentiation and assimilation. Loewinson-Lessing called his petrogenic scheme a "syntectic-liquation theory of differentiation."[1] Since it is the only published, systematically developed scheme at all comparable to that sketched in this book, it will be discussed in some detail. A summary of Loewinson-Lessing's position may be given in his own words, occurring in a recent paper.

"1. The method hitherto adopted of calculating the average composition of the terrestrial magma must be considered as erroneous in principle.

"2. Nevertheless these calculations give a fairly good result, as it corresponds approximately to the mean between gabbro and granite, if we admit that these two magmas enter into the composition of the external part of the earth's crust nearly in equal quantities.

"3. Two original independent magmas exist which predominate in the composition of the earth's crust, the granitic and the gabbroidal (basaltic); all the other igneous rocks are derivates from these two and are subordinate to them in their occurrence.

"4. Differentiation is produced in two ways: during the crystallization, differentiation by crystallization; and before crystallization, in the liquid magma—magmatic differentiation.

"5. The differentiation by crystallization consists in the sinking or rising of the newly formed minerals according to their specific gravity, and in the solution in one part of the magma (generally a deeper-seated one) of minerals formed in another part.

"6. Magmatic differentiation consists in the formation of derived magmas (*Spaltungen*), and is governed by the tendency to form eutectic and mono-

[1] Compte Rendu, Congrès Géol. Internat., 7e Session, St. Petersburg, 1899, p. 379.

mineral (or bimineral) magmas. This differentiation is induced by the fusion and assimilation of foreign mineral masses, both igneous and sedimentary.

"7. Differentiation finds its best explanation in the syntectic-liquational hypothesis (fusion, assimilation, differentiation).

"8. All igneous rocks belong to three types: (1) primordial magmas, (2) rocks due to differentiation, (3) rocks produced by mingling of two magmas.

"9. The igneous rocks of all geological periods, presumably from the Archæan, originated principally by the refusion of different parts of the earth's crust. On account of this we meet in successive periods always the same types of rocks. The pre-Archæan igneous rocks (perhaps also a part of those of the Archæan and younger periods) were formed from primordial magmatic masses of granitic and gabbroidal composition."[1]

The starting-point of Loewinson-Lessing's argument is the assumption of two different magmas, independently eruptible during the whole of recorded geological time. "The mutual relations of the eruptive rocks may be explained most satisfactorily by the admission of two primordial magmas." In this he arrives at the same conclusions as that previously reached by Bunsen in 1851 and by Michel Lévy in 1897.

On page 169 of this book we have seen numerical reason for the approximate identity of the arithmetic mean of all the individual rock analyses with the mean composition of average granite and the average basalt (or gabbro). This identity is certainly referable to the predominance of these two types in the world's igneous terranes. Yet it cannot, of itself, prove the existence of independently eruptible granite magma during the post-Keewatin period of the earth's history. The identity of the two means can equally well be explained on the assumption that, during that long interval, the basaltic magma alone has been eruptible because of intrinsic high temperature.

Though several very extensive masses of anorthosite and a few others of gabbroid nature are on record, it is not certain that a single one of them is a true, "bottomless" batholith. Most of them may be merely injected or laccolithic bodies. In any case the relative rarity of large basic batholiths is an assured fact. This feature of the world-map is hard to explain if, as assumed by Loewinson-Lessing, the two primordial magmas co-exist in the earth's "crust" in about equal volumes, unless we also assume that the granitic rocks dominate in the earth's exterior shell and have been generally re-fused in the batholithic basalt. We thus approach one of the leading conclusions on which the present writer's theory has been formulated.

Loewinson-Lessing has not made clear the way in which the pri-

[1] F. Loewinson-Lessing, Geol. Mag., Vol. 8, 1911, p. 297.

mordial magmas are arranged within the earth, but he does state that each is due to the re-fusion of parts of the earth's *solid* crust.

"Different geological data and theoretical considerations lead to the conclusion that the identity of the eruptive rocks of all geological periods can be most satisfactorily explained by the assumption that from the Archæan up to the present the eruptive rocks represent nearly the same material, which has been subjected several times to weathering, metamorphism, refusion, and regeneration. The assumption that we find or can find anywhere the primordial solid crust of the globe m st be definitely abandoned. The occurrence of clastic and sedimentary rocks in the oldest Archæan formations and numerous examples of refused and recrystallized rocks in these formations eloquently sustain and complete the theoretical considerations which lead us to the conception that the primordial crust has been re-melted long ago, and probably more than once. Such a fusion of parts of the solid crust is sometimes directly attributable to a rising of the isogeotherms at the places in question. In reality the process may be a more complicated one, as can be shown by the following considerations. A series of sedimentary rocks, 30,000 feet thick (the greatest thickness we can admit) would simply by the rising of the isogeotherms acquire in the lowest beds a temperature of 300° C., which is quite insufficient for melting these materials. But the geosyncline, where sedimentation of our 30,000 feet of sediments has taken place, may itself consist of an older series of sedimentary material. At a depth of 60,000 feet under the bottom of our geosynclinal the temperature would be 600° C. before sedimentation, and would rise to 900° C. after the deposition of 30,000 feet of sediments. Under the weight of this new sedimentary sheet of 30,000 feet the area in question would probably bend and subside; this would give for a presumable subsidence of 10,000 feet a further increase of 100°, and so the primary temperature would in this way rise from 600° to 1,000° C. All these figures are, of course, hypothetical. But we must bear in mind that epeirogenetic and orogenetic movements can occasion a far greater subsidence of parts of the crust than the process of sedimentation by itself. It is also not to be forgotten that in these great depths the magma is probably rich in water and different gases, and consequently fusible at a lower temperature than the 'dry' magmas generally considered. And, lastly, we must also infer with Suess that the fusion of certain parts of the earth's crust may be produced partly by the rising from below of hot plutonic gases. In short, there are sufficient factors for sustaining the hypothesis that in successive geological periods different parts of the solid crust have been caused to melt, and that by this process have been generated the plutonic and volcanic rocks.

"When such a refusion or 'anatexis,' as it is called by Sederholm, embraces a portion of the crust, which consists of definite eruptive rocks, *e.g.*, granite, gabbro, basalt, the resulting magma will again be after consolidation the same rock, perhaps only slightly modified by the assimilation of other material during the passage of the magma to the place where it consolidates. But when the remelted portion of the crust is composed of different rocks, eruptive or sedimentary, or both together, the process is rather a 'syntexis,' as I have called it, an assimilation which is followed by liquation and differentiation; the same process of 'syntexis' or assimilation must take place at the margins of such remelted portions where they are in contact with non-melted portions. Although I am an advocate of the hypothesis of a fluid nucleus, I do not believe that this nucleus would have been (perhaps with a few exceptions) the source of the Archæan and post-Archæan intrusive bodies and superficial volcanic masses; but certainly it must be admitted that different portions of the solid or anatectic crust can be mixed during the process of refusion with fluid material coming from peripheric magmatic basins."[1]

From the relative emphasis noted in this passage it is fair to suppose that the author is most inclined to explain local re-fusion of the solid crust by sedimentary blanketing. However, his calculation itself shows the straits into which the advocates of this time-honored suggestion are driven. It is needless to rehearse all the obvious geological facts which show sedimentary blanketing to be merely a *secondary* cause of the heat in eruptive magma. The hypothesis entirely fails to account for the vast number of liquid masses which have been erupted in regions of little or no sedimentation. Examples at first hand may be seen in the fissure eruptions of the Deccan, the long volcanic chain of East Africa, the vulcanism of central France, and that of Greenland. The long chains of enormous volcanoes built on the floor of the Pacific basin can hardly represent fusion under geosynclinal prisms of notable thickness. In many cases geosynclinal downwarping may *begin* with magmatic intrusion (See Table IX, page 186), so often, indeed, that it seems likely that subterranean movement of magma is largely responsible for the formation of geosynclinals.

The appeal to fluxing by plutonic gases is little safer. It must be remembered that a gas, reaching a region of lessened pressure, is bound to expand and cool. Calculation shows that to supply only the latent heat required to melt 100 cubic miles of crystallized basalt would demand the localization of a stupendous quantity of juvenile gas under great pressure. If the magma so prepared were to break through to the earth's surface, the accompanying gas pressure must produce explosions beside which that at Krakatoa would be insignificant. Yet most of the world's basalt has been extruded quietly.

It seems necessary to conclude that the imagined mechanism for the supply of magmatic heat is insufficient for the requirements of igneous geology; yet the petrogenic problem is, at bottom, a heat problem.

Even granting the possibility of local re-fusions of solid basalt and granite (perhaps with the aid of the heat evolved in radioactivity) on the scale demanded, the observed field relations of the igneous

[1] F. Loewinson-Lessing, Geol. Mag., Vol. 8, 1911, pp. 294–295.

rocks and the observed sequences in their eruption cannot be adequately explained. We have here a major difficulty like that faced by the theory of differentiation as the sole explanation of igneous rocks. No one has yet conceived the arrangement of local reservoirs which could erupt, with repeated alternations and in one small region, magmas belonging to the granite and gabbro (basalt) clans. Yet such magmatic successions have often been recorded. If a reservoir of molten basalt underlies one of molten granite, it is inconceivable how the pure basalt could reach the earth's surface. The same elementary difficulty applies if the order of the reservoirs was reversed; and we are in about as much trouble if they are side by side, though separated by a necessarily thin partition. This argument is perfectly general. It applies even to the case of the Keewatin and other early pre-Cambrian basalts. Is there any escape from the conclusion that these basic extrusives traversed a solid, *fissile* earth's crust?

The theory outlined in this book is thus believed to have some advantages over that proposed by Loewinson-Lessing, whose notable and inspiring statement represents the only other published attempt to form a *complete* explanation of the diversity of igneous rocks. Von Cotta's early suggestion, that a basaltic substratum includes all the independently eruptible matter in the earth, has the merit of simplicity. One can *imagine* the mechanism. Its working can be deductively studied and inductively tested. It is economical in its demands on terrestrial heat. No further theory can dispense with at least one assumption as fundamental. No future theory can stand unless the deductions from its basal postulates are likewise matched by the observable facts.

Genetic Classification of Igneous Rocks

Before passing to a further testing of the writer's eclectic theory, it will be well to summarize it once again in terms of the origin of the individual clans of igneous rocks. The following table names those clans whose genesis has been stated or implied in the preceding pages; other clans are credited with origins which are not directly implied by the basal premises of the theory. After the reader has mastered the facts recorded in the next eight chapters, he may be better able to tolerate the boldness of attempting a genetic classification of igneous rocks even in this day of confessedly limited knowledge of the earth.

MAGMAS MAY BE CLASSIFIED AS:

Magma	Representative rocks
1. Primary basaltic	Gabbro clan in general.
2. Primary granitic	? Perhaps only represented in the "anatectic" (refused) form of Laurentian and other pre-Cambrian batholiths.
3. Direct differentiates of primary basalt.	Pyroxene andesite, anorthosite; certain members of the peridotite clan; some iron ores and sulphides.
4. Syntectics, three classes:—	
A. Chiefly composed of basalt and earth's acid shell.	Some members of the diorite clan.
B. Chiefly composed of basalt and sediments.	Rare hybrid types.
C. Composed of basalt, sediments, and acid shell.	Rare hybrid types.
5. Differentiates of syntectics of class A.	Most rocks of the granite clan. Some rocks due to gaseous transfer.
6. Differentiates of syntectics of class B.	Abnormal granites; most of the nephelite and leucite rocks; some corundiferous types; etc. Many rocks due to gaseous transfer.
7. Differentiates of syntectics of class C.	Granodiorite clan for the most part; some members of the syenite clan; etc. Many rocks due to gaseous transfer.
8. Mixtures of two or more of abovementioned types of *liquids*.	Some hybrid rocks?
9. Transition magma marking incomplete differentiation.	Many "intermediate" types.

PART III

CHAPTER XV

GABBRO CLAN

Included Species

The gabbro clan includes the gabbro family, the gabbro-porphyrite family, and the family of the basalts, melaphyres and diabases. According to the last (1908) edition of Rosenbusch's "Mikroskopische Physiographie der Massigen Gesteine," these families are made up of more than 50 types. The species may be listed as follows:

Plutonic Types

Normal Types:

- Gabbros,
  - Olivine gabbro, some hyperites.
  - Olivine-free gabbro.
- Norites,
  - Olivine norite, some hyperites.
  - Olivine-free norite, labradorite norite, bronzite gabbro.
- Anorthosites,
  - Anorthosite proper.
  - Olivine anorthosite.

Aberrant Types:

- Quartz gabbro, quartz norite.
- Hornblende gabbro.
- Mica gabbro.
- Orthoclase gabbro, perthitophyre, gabbro-syenite
- Troctolite, krageröite.
- Oligoclasite.
- Andesinfels.
- Kyschtymite.

Dike Types

- Gabbro porphyrite, microgabbro
- Some augite porphyrites.

Effusive Types

Normal Types:

- Basalts,
  - Olivine basalt.
  - Olivine-free basalt.
    - Hypersthene basalt.
    - Enstatite basalt.
    - Hyalobasalt.
    - Tachylite.
    - Palagonite.
    - Schalstein.
- Melaphyres,
  - Olivine melaphyres, olivine tholeiite
  - Tholeiite.
- Diabases,
  - Olivine diabase.
  - Olivine-free diabases.
    - Palatinite.
    - Leucophyre.
    - Epidiorite.
    - Proterobase.
    - Salite diabase.
    - Hunne diabase.
    - Ophite.
    - Diabase porphyrite.
    - Spilite.
    - Hyalodiabase.
    - Variolite.
    - Kinne diabase.
    - Hellefors diabase.
    - Aasby diabase.
    - Särna diabase.
    - Ottfjäll diabase.

Aberrant Types:

- Iron basalt.
- Quartz basalt.
- Quartz diabase.
- Konga diabase.

Mere differences in geological age or minor differences in rock structure, in degree of crystallinity, and in degree of alteration by weathering or metamorphism, have prompted the invention of at least half the names in this long list. For the purposes of petrogenesis we shall lay especial emphasis on the important chemical contrasts and in a few cases on mineralogical peculiarities.

Primary Basaltic Magma

On reference to Cols. 51-62 of Table II, it will be seen that the respective average analyses of basalt, diabase, olivine diabase, melaphyre, gabbro, olivine gabbro, norite, and olivine norite are very similar. Average extrusive basalt is slightly higher in silica, soda, and potash, and lower in magnesia and lime, than average gabbre. These contrasts are analogous to those generally seen between a plutonic type and the corresponding extrusive type. In fact, the many basalts actually averaged include some types verging on augite andesite, which seems to be best interpreted as a differentiate of basalt. (See Chapter XVII.) In order to estimate more nearly the composition of primitive basalt, the writer has calculated the average of the 198 extrusives of Col. 53, Table II, and the 17 olivine gabbros of Col. 60. Even after the inclusion of these gabbros, the resulting average may still show a slight excess of the alkalies above the proportions characterizing the quite undifferentiated basaltic magma.

The computed average is as follows:

		Water-free
SiO_2	48.84	49.65
TiO_2	1.35	1.37
Al_2O_3	15.90	16.16
Fe_2O_3	5.23	5.31
FeO	6.30	6.40
MnO	.29	.29
MgO	6.38	6.48
CaO	9.15	9.30
Na_2O	3.05	3.10
K_2O	1.46	1.48
H_2O	1.60	.....
P_2O_5	.45	.46
	100.00	100.00

The calculated composition of the primary basalt will be used in the discussion of the other igneous clans as well as of certain types of the gabbro clan. Deviations in the percentages for individual oxides from the true values for the substratum magma must be relatively small and they are not likely to affect the following applications of petrogenic principles.

Normal Olivine-free Species

A moderate amount of olivine would normally crystallize from a magma of the composition above stated, giving olivine-bearing basalt, diabase, and gabbro. Slight gravitative differentiation, whereby the olivine substance (with other femic constituents) settles in the magmatic column, must tend to produce a corresponding olivine-free basalt, diabase, or gabbro in the upper part of each column, and a corresponding olivine-rich pole in the lower part. There are good grounds for believing that this simple mechanism has been partly responsible for the range of mineralogical (and chemical) composition found in the gabbro clan.

Lewis has well illustrated the case in his study of the intrusive Palisade sheet of New Jersey in which olivine-free diabase overlies olivine-rich diabase.[1] Du Toit has found a similar relation between olivine-free gabbro and olivine gabbro in the great Insizwa intrusive sheet of East Griqualand.[2]

It is highly probable that simple gravity has caused the simultaneous development of olivine-free basalt and olivine-rich basalt in volcanic vents.[3] The problem of origins is here evidently much more difficult of solution than it is in the case of well-exposed intrusive sheets; yet the constantly recurring association of both magmatic types in the basaltic fields clearly implies incipient differentiation of a primitive homogeneous magma in each field.

Automatic changes in bodies of the primary basalt are competent to explain these half dozen species in the gabbro clan.

A brief discussion of some other types in this clan is especially demanded since the processes of their formation directly concern the theory of the other rock clans, as more fully stated in the following chapters.

Quartz Diabases and Their Allies

At intervals during the last few years several authors have emphasized the widespread distribution of rocks which are chemically near typical basalt, and yet contain more or less free quartz along with minerals characteristic of basalt or its intrusive equivalents. These types include the quartz diabases, quartz dolerites, quartz gabbros, some quartz-bearing porphyrites, and quartz basalts. Well known examples are: the Konga diabase of Fennoscandia; the Svir diabases

[1] J. V. Lewis, Ann. Report, State Geologist of New Jersey, for 1907, p. 131.
[2] A. L. du Toit, 15th Ann. Rep., Geol. Comm. Cape of Good Hope, 1910, p. 111.
[3] R. A. Daly, Jour. Geology, Vol. 19, 1911, p. 305.

of Russian Karelia; the quartz diabases of many areas in the British Islands; the quartz dolerites of the Karroo and other districts of South Africa; the quartz diabases, quartz porphyrites, and quartz basalts of California; the quartz diabases and quartz dolerites of Antarctica, Central Australia, and Western Australia; the quartz diabases of Cutch and Southern India, of Northern Siberia, of the Congo Free State and British Guiana; the quartz diabases of Arran, Greenland, Sumatra, and other large islands; the quartz diabases and quartz gabbros of British Columbia, Minnesota, Michigan, Ontario, and Quebec; etc.[1]

Other types of similar, or but slightly different, magmatic character are: quartz norite, some orthoclase gabbros, and some mica gabbros. These rocks are unlike normal basalt, diabase, or gabbro, in containing free silica; many of them have a decided tendency to crystallize with micropegmatite interstitially developed. Some authorities have attributed certain of the types to the slight acidification of ordinary basaltic (gabbroid) magma through the solution of silicious country rocks. The present writer believes that this hypothesis may be fruitfully applied to all of the rocks above listed.

The dominant hypothesis has long held that the quartz diabases and their magmatic allies have crystallized directly from a primeval magma. Recently, Wahl and Thomson have stated their adherence to this view.[2] Their evidence is, however, not conclusive and there are several strong grounds for belief in a secondary origin for the whole group of species.

It is noteworthy that the quartz diabases and their allies are not known in the deep-sea islands, that is, in the multitude of volcanoes which have been built up in areas outside the continental plateaus or the more or less submerged parts of those plateaus. In the same, truly oceanic region of the globe there is likewise an entire absence of outcrops of acid sediments, acid crystalline schists, and granitic terranes, although normal basalt is represented in most of the oceanic volcanoes. These contrasts of distribution are difficult to explain if the quartz-diabase magma is an independent, primitive constituent of the earth.

Secondly, these quartz-bearing rocks are almost always in intimate field association with normal basaltic, diabasic, or gabbroid rocks. The relation is often one of gradual transition, or otherwise such as to render the hypothesis of mutual independence thoroughly improbable;

[1] See the many references given in Zirkel's Lehrbuch der Petrographie; in Rosenbusch's Mikroskopische Physiographie der Massigen Gesteine; in the papers by Tyrrell and Thomson noted below; and in the next chapter.

[2] W. Wahl, Fennia, Vol. 24, No. 3, 1908, p. 69; J. A. Thomson, Proc. Roy. Soc., New South Wales, Vol. 45, 1912, pp. 311–315.

the mechanism by which the two primitive magmas could be kept separate until the time of actual eruption has never been described.

Thirdly, not only are all the known bodies of the quartz diabases and their allies erupted through or into terranes more silicious than primary basalt; many, if not most, of the intrusives are of comparatively large size. This fact is explicable and expected on the syntectic theory; it fails of explanation on the alternative, older view.[1]

But, finally, the compelling argument is to be found in an analysis of those cases where large bodies of micropegmatitic granite have clearly been formed by the solution of acid terranes in normal basaltic magma. This subject is discussed at length in the next chapter, where it will be seen that many quartz diabases, quartz gabbros, quartz dolerites, etc., are transitional into secondary granites which are chemically and mineralogically consanguineous with their respective country rocks.

The solution of the acid wall-rock, forming a syntectic of the quartz-diabase type, may take place during the steady or intermittent rise of the substratum material in the act of eruption, or, in part, it may take place after the magma has found its final position in the earth's crust, as sill, laccolith, or dike. There is reason to believe that the former method of acidification has often operated so that it is impossible to test the measure of consanguinity between syntectic and country rocks, which must in most cases be themselves of varied composition. Nevertheless, cases favorable for this test are already known in number sufficient to warrant belief in a syntectic origin for quartz diabases and their chemical equivalents.

NORITES

Rosenbusch points out that the norites and olivine norites are generally found only in close geological association with gabbros; that the norites are transitional into gabbros and olivine norite on the one hand, and into mica-hypersthene diorite and quartz-mica-hypersthene diorite on the other; and that the norites are somewhat more acid than the gabbros.[2] Column 51 of Table II shows that the average of the available analyses of norite (calculated as water-free) has about 1 per cent. more silica than average "primary basalt." Quartz and biotite, or hornblende, are common accessories and at Sudbury, in the Insizwa Mountains, Cape Province (see page 232), and at other well known localities, norite passes into quartzose or granitic types.

[1] Cf. R. A. Daly, Amer. Jour. Science, Vol. 20, 1905, p. 215; G. W. Tyrrell, Geol. Mag., Vol. 6, 1909, p. 363.

[2] H. Rosenbusch, Mikroskopische Physiographie der Massigen Gesteine, 4th ed., 1907, p. 348.

Prior has suggested that the norites or coarse-grained enstatite-dolerites of the Umqueme Range, Zululand, "might very well be more deeply seated rocks derived from the same magma which supplies the dolerites" of the region. In the next chapter (see page 350) will be found a statement of the probability that these dolerites have absorbed the invaded sandstones on a comparatively large scale.[1] From the facts in hand we may fairly entertain the hypothesis that most of the norites have crystallized from basaltic magma which has dissolved minute proportions of acid country rock. This explanation will not suffice, however, for certain so-called norites very low in alkalies or otherwise peculiar. In both chemical and quantitative mineralogical composition these types must have originated differently from the average norite.

Hypersthene Basalts and Enstatite Diabases

These types are respectively connected with normal basalt and diabase by transitional, often olivine-bearing, rocks. In part they clearly represent differentiates of primary basaltic magma, not essentially affected by the solution of foreign material, and thus mark the way to the pyroxene andesites. But in part they seem to match the theoretical deduction that acidification of primary basalt should cause the generation of orthorhombic pyroxene in place of olivine. Rosenbusch has listed some of the occurrences of hypersthene-bearing and enstatite-bearing diabases which also carry granophyric (micropegmatite) material. These rocks are thus true quartz diabases or else merge into them. So far as recorded, the field relations justify the hypothesis that these particular hypersthenic and enstatitic species, like their near relatives the acid norites, illustrate syntectics of basaltic magma and acid country rocks.

Hornblende Gabbros

This group is not largely represented in igneous terranes, but it offers a special problem which arises also in a detailed genetic study of some other members of the gabbro clan, *e.g.*, certain norites. It is characteristic of these rocks that the alkalies are decidedly less abundant than in primary basalt, while other oxides are present in nearly the same proportions as in the basalt. The writer will hazard a suggestion as to the genesis of one type of the hornblende gabbros, a type which he has studied in some detail.

The dominant rock in the Purcell sills of British Columbia is one of these abnormal gabbros, with composition as follows (Col. 1):

[1] G. T. Prior, Annals Natal Museum, Vol. 2, 1910, p. 147.

	1	2	Mode of 1	Per cent.
SiO_2	52.94	48.84		
TiO_2	.73	1.35		
Al_2O_3	14.22	15.90		
Fe_2O_3	2.08	5.23		
FeO	8.11	6.30	Hornblende	54.8
MnO	.35	.29	Labradorite	25.6
MgO	6.99	6.38	Quartz	6.3
CaO	10.92	9.15	Titanite	2.0
Na_2O	1.40	3.05	Magnetite	.3
K_2O	.49	1.46	Chlorite	11.0
H_2O-	.12	1.60		
H_2O+	1.56			100.0
P_2O_5	.08	.45		
	99.99	100.00		

Column 2 gives the composition of the theoretical "primary basalt" of the substratum. The sills and their feeding dikes cut silicious sediments of enormous thickness. As noted in the next chapter, the basic magma has absorbed some of the quartzitic country rock. It must, therefore, have absorbed water and other volatile substances originally enclosed in the sediments. Many batholithic contacts show that magmatic water has the power of transferring part of the alkalies out of the magma chamber. Granting that this has occurred to a considerable extent in the Purcell magma, its chemical contrast with, and derivation from, the primary basalt can be understood. The specially great abundance of microperthite in the thick hornfelses at the *roofs* of these sills is in part explicable on this hypothesis of gaseous transfer, though in part the alkaline feldspar is indigenous to these quartzites. The presence of considerable water in the magma is suggested by the presence of hornblende itself, the crystallization of which, as experiments show, seems to demand that water be in the solid amphibole solution.[1] Excepting the silica, the residue of the (primary) basaltic magma has the proper composition after subtraction is made of the feldspar molecules to the required amount. The deficiency of silica in the residue has, on the initial hypothesis, been supplied by a slight assimilation of the invaded quartzite. (See Fig. 158.)

This explanation is not contravened by the facts now known about the Purcell rocks, but it is advisedly described as a preliminary guess at the solution of a difficult question. It has, however, the value of facilitating belief in a secondary derivation of the abnormal gabbro from the normal basaltic magma. In fact, Schofield reports the occurrence of more normal gabbro among the Purcell sills which he has specially studied.

[1] E. T. Allen and J. K. Clement, Amer. Jour. Science, Vol. 26, 1908, p. 118.

An analogy is to be found in many quartz diabases which are characteristically low in alkalies and tend to be low in alumina. An example is seen in the analyses of the diabases of Kusjkin Island, Siberia, by Backlund.[1] As shown in the next chapter, the evidences are weighty that quartz diabases are generally developed as syntectics of basaltic magma and wet, acid sediments. The chemical contrast of these igneous rocks with primary basalt is also in part explicable by the influence of absorbed water.

Iron Basalt

In his handbook Rosenbusch devotes much space to a discussion of the celebrated Greenland basalts carrying segregations charged with metallic iron. He notes their special importance for his general hypothesis that igneous rocks have been derived from metallic alloys (*Kerne*). On the other hand, Zirkel favors Törnebohm's suggestion that this iron is due to reduction of the iron oxides in an originally normal basalt.[2] The reduction is ascribed to the absorption of carbonaceous matter from bituminous sediments traversed by the basalt.[3] In his more recent study of the problem, Schwantke has indicated the probability of the derived origin through the reducing action of foreign carbon.[4] The close field association of "graphite basalt" with the Greenland iron-bearing rock distinctly favors this explanation. Quite recently Benedicks has shown that the Ovifak iron is a true natural steel, thus powerfully sustaining Törnebohm's view.[5]

Anorthosites

Many bodies of anorthosite are so enormous that several of their special students have been led to describe them as batholiths, thereby implying that their mechanism of intrusion is like that of the greater masses of granite. If this were proved to be true, the basal conceptions of the eclectic theory would need drastic revision. Batholithic granite has been interpreted as a differentiate of crust materials dissolved in large abyssal wedges injected from the basaltic substratum. The emplacement of batholiths at visible levels is credited to this assimilation. Since the anorthosites of the world regularly cut rocks much more acid than themselves (gneisses, acid schists, etc.) it would seem inevitable that, if they were emplaced by assimilation, their chemical com-

[1] H. Backlund, Mem. Acad. Imp. Sciences, St. Petersburg, Vol. 21, 1910, p. 25.

[2] A. E. Törnebohm, Bihang, Svenska Vet. Akad. Handlingar, Vol. 5, 1878, p. 16.

[3] F. Zirkel, Lehrbuch der Petrographie, 2nd ed., Vol. 2, 1894, p. 894.

[4] A. Schwantke, Sitzungsber., Akad. Wiss., Berlin, Vol. 50, 1906, p. 853.

[5] C. Benedicks, Compte Rendu, Congrès Géol. Internat., 11th session, Stockholm, 1910 (1912), p. 885.

position would not be that of a labradorite-rock. It is, therefore, a matter of importance that many field evidences indicate an injected, *laccolithic* origin for most or all known bodies of this rock. On account of the critical nature of the subject, in relation to petrogenic theory, these evidences will be noted in some detail.

Abnormal Features of the Anorthosites.—As already observed, most plutonic or granular igneous rocks are represented in pre-Cambrian eruptions, as well as in eruptions of post-Cambrian time, including the Cenozoic era. The larger anorthosite masses are unique in having eruptive dates almost entirely, if not quite, in the pre-Cambrian. This fact is illustrated in the following table (XVI) showing the principal outcrops of the rock.

The only large bodies not assigned definitely to the pre-Cambrian are those of Norway. Kolderup states that the latter cut the fossiliferous "Silurian" schists near Bergen, but it is not made clear in his memoirs that the labradorite-rock itself is in this relation. The published map of the Bergen masses show them to be entirely enclosed in the pre-Cambrian terrane. Gabbroid rocks do cut the Silurian beds but it is not rendered certain to the reader of Kolderup's papers that these gabbros are contemporaneous with the anorthosites.

However this may be, no very large body of anorthosite dating from the later Paleozoic, Mesozoic, or Cenozoic time has yet been reported. It seems as if the generation of the greater massifs of this rock were due to the special conditions obtaining in an early stage of the earth's history. This stage is, however, not the earliest, for every described body of anorthosite seems to be younger than the oldest greenstones and associated granites of the pre-Cambrian basement complexes. The greatest and most numerous bodies of all have been assigned by Adams to the "Upper Laurentian."

A second point of contrast with the other plutonic types is seen in the fact that the anorthosites do not seem to be represented by effusive equivalents. This characteristic is undoubtedly significant. In view of the large size of the anorthosite bodies one might expect their magmas occasionally to penetrate the roofs and issue as flows or breccias. The absence of these cannot be attributed to removal by erosion, for that would imply a perfect denudation not matched in the normal batholithic-volcanic associations of the pre-Cambrian. On the contrary, *at the time when each anorthositic magma as such originated*, it appears to have lacked the power to reach the surface through fissure or diatreme. This suggests some special property of the magma, such as high viscosity or a minimal charge of the gaseous constituents necessary for continued volcanic action. As we shall see, there is good evidence of high viscosity in several of the greater masses at the time of intrusion.

TABLE XVI

Region	Approximate area Square miles	Date of intrusion
Labrador peninsula, 17 large bodies (total area about 50,000 sq. miles.)	....	Pre-Cambrian
Saguenay district, Quebec................	5800	Pre-Cambrian
St. Urbain district, Quebec (body 70 miles long).	....	Pre-Cambrian
Morin district, Quebec...................	990	Pre-Cambrian
Ten smaller areas between Three Rivers and Montreal, Quebec.	....	Pre-Cambrian
Kildare, Cathcart, and Brandon townships, Quebec, 5 small bodies.	....	Pre-Cambrian
Chibougamau district, Quebec.............	100	Pre-Cambrian
Moisie River, Quebec....................	....	Pre-Cambrian
St. George's Bay, Newfoundland (area 60 miles long.)	....	?
St. John, New Brunswick (small body)....	....	?
Adirondacks, New York..................	1200+	Pre-Cambrian
Northern New Jersey (small body)........	....	?
North Carolina (small body).............	....	?
Glamorgan township, Ontario (small body)	....	Pre-Cambrian
Georgian Bay, Ontario..................	....	Pre-Cambrian
Thunder Bay district, Ontario (small body)	....	Pre-Cambrian
Rainy Lake district, Ontario..............	25	Pre-Cambrian
Sherman Quadrangle, Wyoming...........	52	Pre-Cambrian
Upper St. Joe River, Idaho...............	5+	Pre-Cambrian (?)
Southern Vancouver Island...............	10+	Late Mesozoic
Bergen district, Norway..................	18+	Silurian or post-Silurian (?)
Bergen district, Norway..................	60+	Silurian or post-Silurian (?)
Bergen district, Norway..................	4	Silurian or post-Silurian (?)
Ekersund-Soggendal district, Norway......	400	Silurian or post-Silurian (?)
Voss-Sogn district, Norway...............	800+	Silurian or post-Silurian (?)
Lofoten Islands..........................	....	?
Angermanland, Sweden..................	....	Pre-Cambrian
Volhynia, Podolia and Cherson districts, Russia ("large massifs")	....	Pre-Cambrian
Island of Skye, local differentiates........	....	Tertiary
Island of Rum, local differentiates........	....	?
Raniganj coal-field district, India..........	....	Pre-Cambrian
Natal-Zululand..........................	....	Phases of sills cutting Permian strata.
Egypt..................................	....	Probably pre-Cambrian.

A third abnormality is the very coarse grain generally characteristic of these rocks. The grain has evidently been controlled in part by the existence of a cover in each case; in other part it is due to the monomineralic nature of the magma, with its almost infinite concentration of the feldspar molecule.

Anorthosite a Differentiate of Gabbro.—Most petrographers agree that anorthosite is a direct derivative of gabbroid (basaltic) magma. The full story of mineralogical and chemical resemblances, of transitional phenomena, and of intimate field association, need not be told here, but certain field illustrations will be recalled in order to indicate the probable modes of differentiation.

That the splitting of anorthosite from originally gabbroid magma occurs in true injected bodies of the sheet type is abundantly proved. When these masses are fairly thick, the gabbro shows a general tendency to become banded, with the separation of highly feldspathic (labradoritic) layers from more femic layers. This segregation is sometimes accomplished in place. On the other hand, Geikie and Teall have given reason for the belief that the well known sills of the Cuillin Hills, Island of Skye, are banded because of the intrusion of gabbro magma differentiated at lower levels and then injected as a heterogeneous mixture of salic (anorthositic) and femic magmas.[1] Similarly, Harker has interpreted the alternating sheets of peridotite and "allivalite" (anorthositic rock) of the island of Rum as distinct intrusions of formerly gabbroid magma, made heterogeneous by spontaneous splitting in depth. He notes that even these partial magmas were themselves heterogeneous, so that an individual sheet is conspicuously banded with more feldspathic and more olivinitic layers. From his description it appears that the differentiation was progressing *during* the steady or intermittent rise of the original magma. It continued *after* the heterogeneous magma has reached its final position, for salic and femic materials are still further segregated in "concretionary structures traversing the various bands." The magmatic splitting was here, then, partly in place, and partly preliminary to injection into the visible *sill chambers.*[2]

The vast laccolith of Duluth gabbro is locally banded, again with anorthositic facies, but it also displays very large segregations of anorthosite with individual outcrops, each measuring nearly or quite a

[1] A. Geikie and J. J. H. Teall, Quart. Jour. Geol. Soc., Vol. 50, 1894, p. 645. An analogy is found in the remarkable rock group including the recently described "ornöites" of Sweden. (See A. G. Högbom, Bull. Geol. Inst., Upsala, Vol. 10, 1910, p. 149.)

[2] A. Harker, Geology of the Small Isles, Memoirs, Geol. Survey, Great Britain, 1908, pp. 69–77; The Natural History of the Igneous Rocks, New York, 1909, p. 140.

square mile in area.[1] In part at least these are regarded as differentiates in place and N. H. Winchell suggests that the splitting was influenced by gravity, which tended to move the feldspathic pole toward the roof (southeastern contact)[2] (Fig. 149). Bowen has recently discovered anorthosite as a differentiate of diabase magma in the sills of the Thunder Bay district, Ontario, and he points to the possibility that

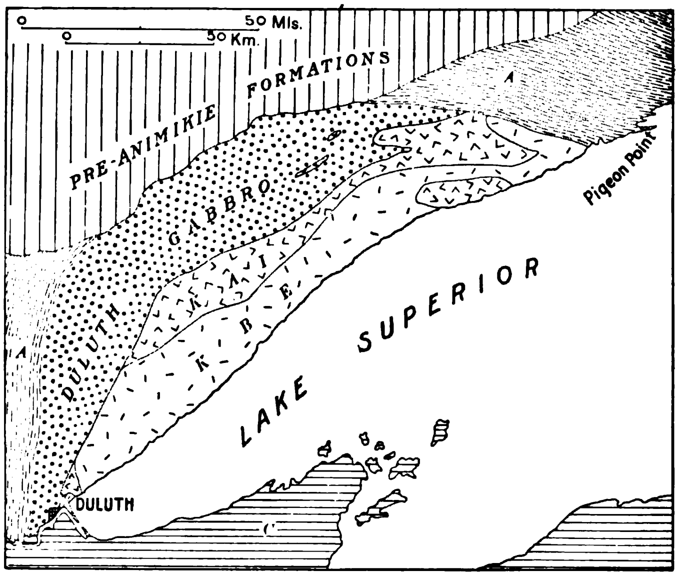

FIG. 149.—Map of the Duluth laccolith. (After C. R. Van Hise and C. K. Leith, Mon. 52, U. S. G. S., 1911.) *A*, Animikie slates, etc.; *KBE*, Keweenawan "basic extrusive;" *KAI*, Keweenawan "acidic intrusive;" *C*, Cambrian and later sediments.

large bodies of anorthosite may be formed by similar splitting.[3] Prior states that the dolerite sills cutting Permian strata of Natal and Zululand have split into anorthositic and pyroxenitic phases.[4]

Very little systematic work has been done to test the hypothesis that this differentiation in gabbro or diabase sheets and laccoliths has been controlled by gravity, but the writer believes that it is a well

[1] N. H. Winchell, Final Report, Geol. and Nat. Hist. Survey of Minnesota, Vol. 4, 1899, p. 302; N. H. Winchell and H. V. Winchell, Bull. 6 of same survey, 1891, p. 126; C. R. Van Hise and C. K. Leith, Monograph 52, U. S. Geol. Survey, 1911, p. 374.

[2] N. H. Winchell, Final Report, Geol. and Nat. Hist. Survey of Minnesota, Vol. 5, 1900, p. 66.

[3] N. L. Bowen, 20th Annual Report, Bureau of Mines, Ontario, 1911, p. 127.

[4] G. T. Prior, Annals, Natal Museum, Vol. 2, 1910, p. 147.

justified conception. This does not mean that *all* of the feldspathic pole should be collected at the roof, for some of its material must be "frozen in" at deeper levels during the splitting and simultaneous crystallization of each mass. Under the circumstances, gravity would merely *tend* to raise the anorthositic material toward the roof and to sink the magmatic complements—peridotites, pyroxenites, iron ores, etc.—toward the floor. A compilation of all the available published data shows that these general tendencies are illustrated in the Duluth laccolith. At intervals along its floor, ultra-femic gabbros, titanic iron

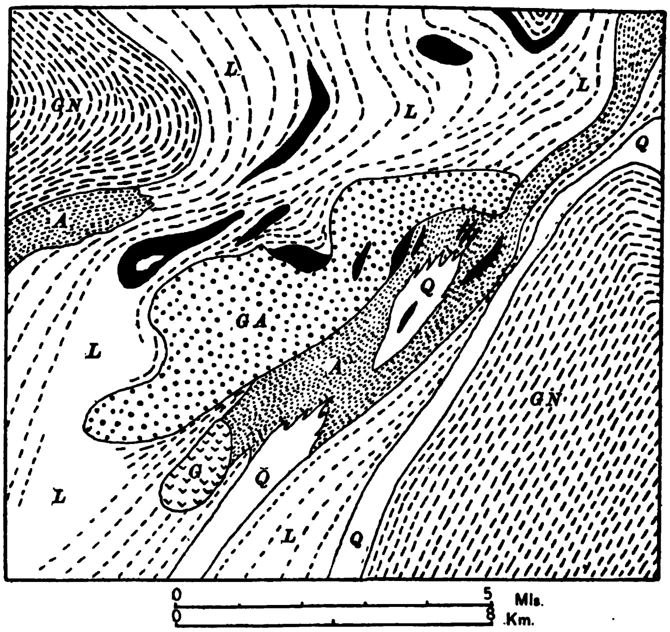

FIG. 150.—Map of the Glamorgan gabbro, Ontario. (After F. D. Adams and A. E. Barlow, Memoir No. 6, Geol. Surv. Canada, 1910.) *L*, Grenville limestone; *A*, amphibolite; *Q*, quartzite and paragneiss; *GN*, granite gneiss (intrusive); *G*, intrusive granite; *solid black*, nephelite syenite; *GA*, gabbro. Strike lines indicated in *GN*, *A*, and *L*.

ores, peridotites, and pyroxenites are well developed; according to Bayley and others, these are differentiates from the laccolithic gabbro.[1]

In the Chibougamau district of Quebec, a body of anorthosite covering somewhat more than 100 square miles presents analogous phenomena. This mass is over 28 miles in length, with a width of from 2 to 5 miles. It has been described as a "batholith," but it has the earmarks of a laccolith, of much smaller size than the Duluth body. Along its northern contact, which is made with Keewatin greenstones, the

[1] W. S. Bayley, Jour. Geology, Vol. 2, 1894, p. 814.

anorthosite has gabbro, basic norite, pyroxenite, and iron-ore facies. Unfortunately, the original roof is not exposed; in its place is a continuous mass of granite which cuts the anorthosite.[1]

Another case where one may suspect gravitative differentiation is found in the intrusive gabbro of Glamorgan township, Haliburton County, Ontario (Fig. 150). This body measures 8 miles in length by 2.5 miles in extreme width. It has been intruded at or near the plane of contact of the great Grenville limestone and a group of amphibolites. The igneous contacts are mapped as concordant with the schistosity, and presumably with the bedding, of these rocks. The relations are apparently those of a laccolith. Along the northern contact, the gabbro passes into pyroxenite, hornblendite, and iron-ore phases; feldspathic phases approaching anorthosite are found near the southern contact. These facts agree with the conception that the mass is a tilted and eroded, differentiated laccolith, but obviously little stress can be laid on this idea until further structural work supplements the reconnaissance of Adams and Barlow.[2]

The greater bodies of anorthosite are exposed in such complicated relation to country rocks and to the present erosion surface that it is impossible to locate roof or floor with precision; but, where the dimensions are large in all directions, it is *a priori* just to consider the outcropping rock as roughly representing the actual area of the roof, which has been eroded away. If gravitative splitting has occurred in these huge bodies, we should expect the differentiation to take place in a manner like that so often seen in true batholiths. (See pages 240–244.) As a matter of fact, the greater anorthosite bodies usually have a well-developed contact phase of more or less typical gabbro or norite. In the interior each mass becomes rapidly more feldspathic and, for most of the outcrop, the rock is monotonous anorthosite. The femic pole has settled to the floor and remains invisible unless (as often happens) a later eruptive effort sends injections of ultra-basic material through the anorthosite or its country rocks.

Illustrations of such gabbroid contact phases as indicators of gravitative differentiation have been noted in the following areas:

1. Morin district, Quebec (Fig. 153).
2. Saguenay district, Quebec (Fig. 156).
3. Rainy Lake district, Ontario.
4. Adirondacks, New York (Figs. 122 and 157).
5. Ekersund-Soggendal district, Norway.

[1] A. E. Barlow, J. C. Gwillim, and E. R. Faribault, Report on the Geology and Mineral Resources of the Chibougamau Region, Quebec, Quebec City, 1911, p. 156.

[2] F. D. Adams and A. E. Barlow, Memoir No. 6, Geol. Survey of Canada, 1910, p. 153.

It remains to note the relation of this splitting to that whereby the pyroxene andesites have also been derived from basalt. In Chapter XVII will be found a brief statement of the conditions under which augite andesite is thus formed. They are the conditions at the vents of volcanic eruptions of the central type, where magmatic gases are specially concentrated, with resulting effect on the chemical process of differentiation. There is no similar mechanism for intense gas concentration in laccoliths, where the salic pole of basaltic splitting may well differ from that at central vents. Other contrasts—different pressures, different lengths of magmatic life, etc.—may also be in control. Where so little is known of the physical conditions of magmatic differentiation it is idle to attempt full analysis of the problem; we may safely rely on the facts of the field as showing that basalt *does* split, more or less spontaneously, into these two very different, more salic submagmas. The recorded field relations seem to be best explained on the theory of gravitative differentiation, where the feldspathic units (probably non-consolute submagmas) have tended to collect at the upper part of each chamber.

Mode of Intrusion.—We have seen that anorthosite has split off from normal gabbroid magma within chambers of the sill and laccolith types. All the clearest illustrations of this segregation have been found in injected bodies of magma, that is, those with solid rock floors. Is it possible to extend that rule to *all* of the larger anorthosite masses of the globe? Obviously the question cannot be answered in full but there are grounds for believing it to be worthy of serious consideration.

A conceivable difficulty in the way of crediting a laccolithic character for such bodies as the Saguenay, Morin, or Adirondack masses is the vast size of each, an area out of all proportion to those ordinarily characterizing laccoliths. Yet it has become gradually clearer that the pre-Cambrian was a time when very large basic injections were comparatively frequent, once more illustrating the fallacy of the strict uniformitarian principle in geology.

In 1899 Grant stated the view that the Duluth gabbro of Minnesota is a laccolith, and he is supported therein by Van Hise and Leith.[1] It was injected along the contact of the Animikie and Keweenawan formations (Fig. 149). Its length is about 125 miles, with a maximum width of about 25 miles and an area of about 2400 square miles. Though locally cross-cutting, its contact planes generally parallel the bedding of the Animikie, giving a concordant relation locally observed in actual outcrops by the geologists of the Minnesota Survey, and suggested in

[1] U. S. Grant, Final Report, Geol. and Nat. Hist. Survey of Minnesota, Vol. 4, 1899, p. 326; C. R. Van Hise and C. K. Leith, Monograph 52, U. S. Geol. Survey, 1911, p. 202.

a map of the whole body. With the average dip of 10°+ estimated from the associated sediments, the thickness of the laccolith at its center is calculated to be over 20,000 feet.

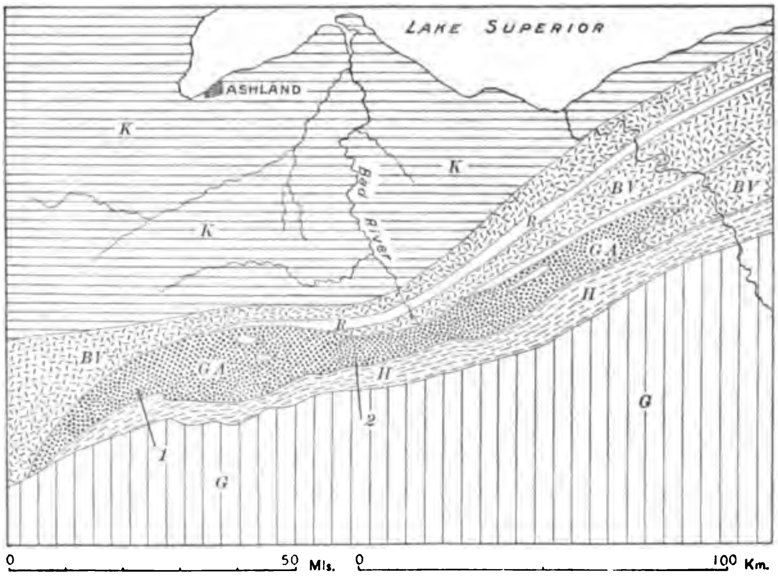

FIG. 151.—Map of the Bad River laccolith, Wisconsin. (Same ref. as for Fig. 149.) *G*, pre-Huronian schists, granite, etc.; *H*, Animikie slates, quartzites, etc.; *BV*, Keweenawan basic volcanics; *K*, Keweenawan conglomerate, sandstone, and slate; *GA*, gabbro laccolith; *R*, "red rock" (granite, etc.).

A similar but less extensive gabbro laccolith has been mapped in the Bad River region of Wisconsin. It is stated to have an outcrop

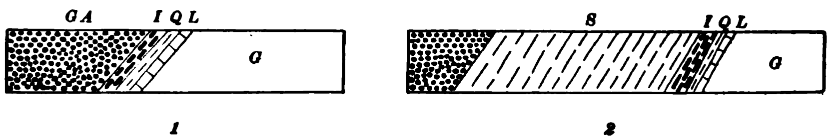

FIG. 152.—Sections at lower contact of Bad River laccolith. (After R. D. Irving and C. R. Van Hise, Mon. 19, U. S. G. S., 1892, Pl. 2.) *G*, granite, gneiss, and schist; *L*, Huronian limestone; *Q*, Huronian slate (quartzose); *I*, Huronian iron-bearing member; *S*, Animikie slate; *GA*, gabbro of laccolith. Scale, 1:100,000.

length of 60 miles, a maximum width of 5 miles and a thickness estimated as between 9500 and 25,000 feet.[1] This body also follows the

[1] C. R. Van Hise and C. K. Leith, op. cit., p. 377. Is the Bad River body merely a part of the Duluth laccolith repeated in outcrop by the great Lake Superior syncline?

basal contact of the Keweenawan series (Figs. 151–2). The structural relations and form are, here again, indications of laccolithic or sheet intrusion and this conclusion is backed up by the local occurrence of numberless clearly understood, basic sills already famous in Lake Superior geology.

The laccolithic or sheet nature of the Sudbury norite is specially well demonstrated, affording still another illustration of the immense scale on which gabbroid magma was erupted into *floored* chambers during the late pre-Cambrian time (Fig. 160, p. 348).

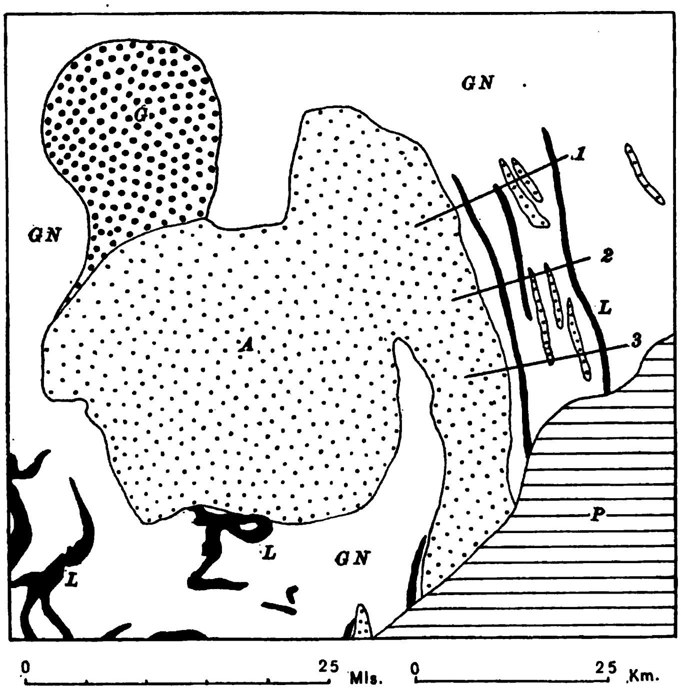

FIG. 153.—Map of the Morin district of anorthosite, Quebec. (After F. D. Adams, Ann. Rep. Geol. Surv. Canada, Vol. 8, 1895.) *GN*, gneiss; *L* (*solid black*), limestone; *G*, gabbro; *A*, anorthosite; *P*, Cambrian and Ordovician strata (overlap).

Some of the gabbro masses of the Adirondacks are definitely described as laccoliths.[1]

Many other gabbroid and anorthosite masses of the pre-Cambrian have not been regarded or described as of laccolithic character and yet they are accompanied by structural features which suggest that origin. Figs. 153 and 154 illustrate the inferred relations of the great

[1] Report of the International Committee on the Pre-Cambrian, Jour. Geology, Vol. 15, 1907, p. 208.

Morin area of anorthosite in Quebec. The concordant relation of the igneous contacts to the bedding of paragneisses and limestone is clearly shown, both for the satellitic sheets or laccoliths and for the main body itself.[1] Adams notes that the Canadian anorthosite intrusions "frequently" take "a line of least resistance" and lie between bands or strata of the Grenville series.[2] The recurrent parallelism of the mapped bands of upturned anorthosite sheets with limestone beds is significant (Fig. 153). Högbom has noted that the gabbro-anorthosite mass of Ångermanland, Sweden, has a "laccolithic" relation to the Archean rocks on the west.[3] The anorthosite areas of the Bergen district, Norway, are very long bands with concordant relations to the enclosing paragneisses and other schists of the pre-Cambrian; the

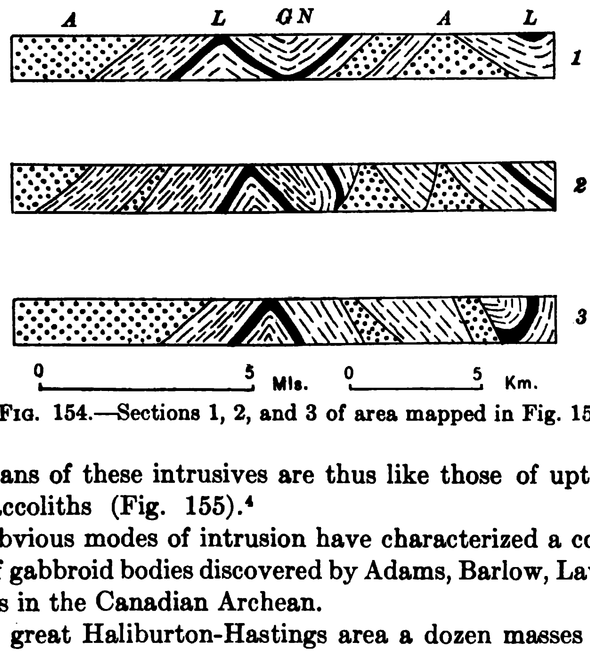

FIG. 154.—Sections 1, 2, and 3 of area mapped in Fig. 153.

ground-plans of these intrusives are thus like those of upturned and eroded laccoliths (Fig. 155).[4]

Less obvious modes of intrusion have characterized a considerable number of gabbroid bodies discovered by Adams, Barlow, Lawson, Low, and others in the Canadian Archean.

In the great Haliburton-Hastings area a dozen masses of gabbro, "diorite," or anorthosite have been mapped. In every case there is marked concordance between igneous contact and the schistosity of the country rocks (limestones, basic eruptives, etc.). In large part this schistosity is parallel to true bedding in the invaded sediments and it is difficult to believe that dynamic metamorphism should have superposed the concordance, to the degree mentioned, on a series of igneous contacts

[1] F. D. Adams, Ann. Rep. Geol. Survey Canada, Vol. 8, Pt. J (map), 1895.

[2] F. D. Adams, Jour. Geology, Vol. 1, 1893, p. 334.

[3] A. G. Högbom, Geol. Fören. Stockholm Förhand., Vol. 31, 1909, p. 366.

[4] C. F. Kolderup, Bergens Museums Aarbog, 1903, No. 12, map.

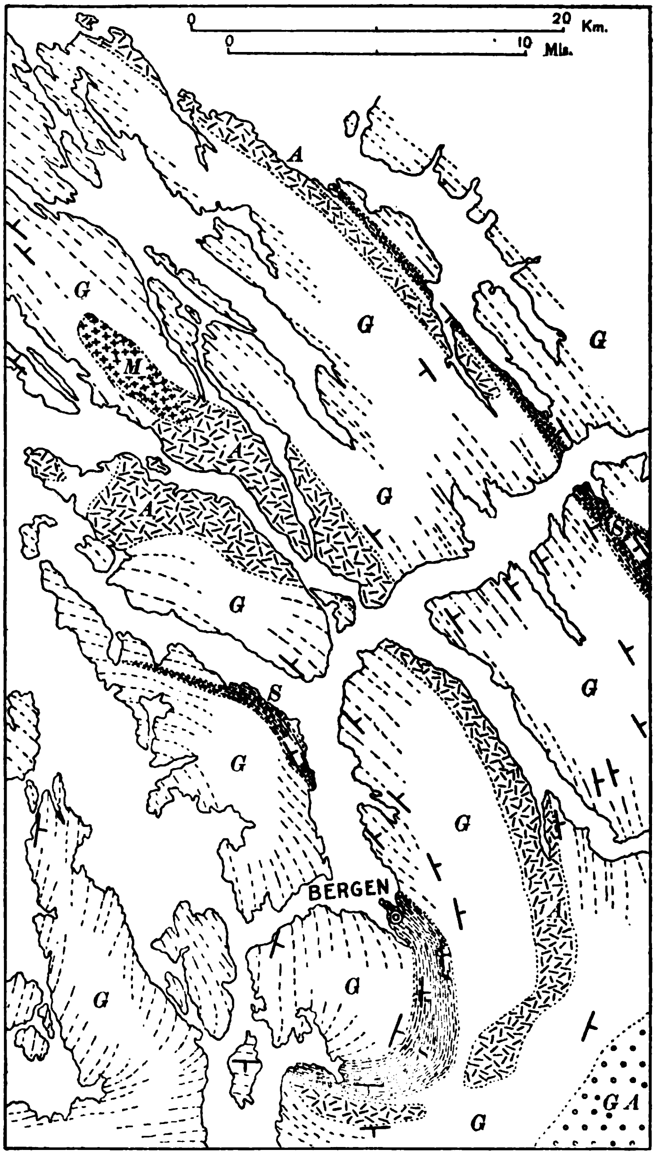

FIG. 155.—Map of the anorthosite areas, Bergen district, Norway. (After C. F. Kolderup, Bergens Museums Aarbog, 1903, No 12.) *G*, gneiss and granite; *S*, Silurian rocks; *A*, anorthosite; *M*, mangerite; *GA*, saussurite gabbro. Symbols for strike and dip.

which were initially cross-cutting.[1] The field relations so far as described seem, therefore, to indicate that these intrusives belong in the injected, laccolithic class, rather than in the subjacent, batholithic class. On this assumption it has been above suggested that the differentiation of the Glamorgan gabbro (Fig. 150) into anorthositic and peridotitic phases has occurred *in situ*. The anorthosite body of of the Rainy Lake region similarly shows almost perfect concordant re-

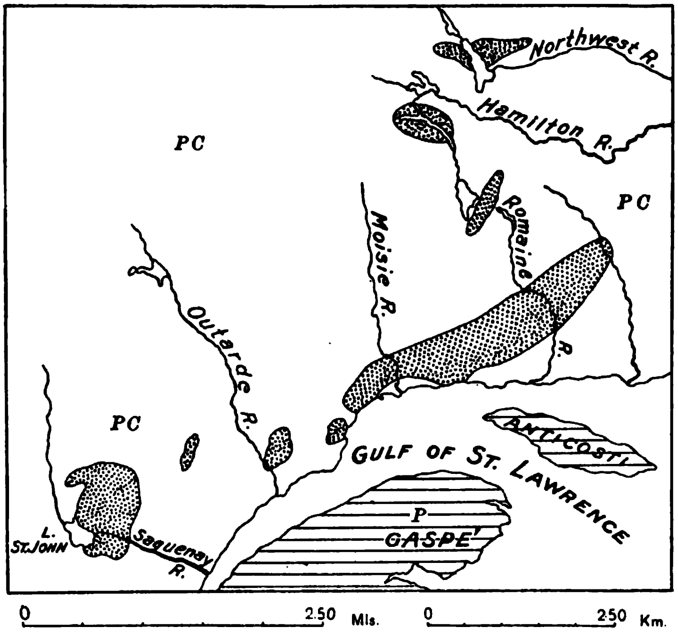

FIG. 156.—Map of anorthosite areas in eastern Canada. (After Atlas of Canada, Interior Dep't of Canada, 1906, Pl. 5.) *PC*, pre-Cambrian gneisses, etc.; *P*, Paleozoic formations; *dotted*, anorthosite.

lations to the surrounding gneisses.[2] We have already noted that the visible original contacts of the Chibougamau anorthosite are concordant with the Keewatin green schists and it is significant that the authors of the report on that district note the occurrence of small laccolithic basic intrusives in the Keewatin terrane.[3]

In fact, it seems to be a general rule that the great basic intru-

[1] F. D. Adams and A. E. Barlow, Memoir No. 6, Geol. Surv. Canada, 1910. See maps and page 31, where these authors state that the banding of the thick Grenville limestones represents bedding.

[2] A. C. Lawson, Ann. Rep. Geol. Surv. Canada, 1887, Pt. F, map and section "K–L" at page 43.

[3] A. E. Barlow and others, Report on the Geology and Mineral Resources of the Chibougamau Region, Quebec, Quebec City, 1911, p. 164.

sives of the pre-Cambrian are accompanied by large and small sills and laccoliths of similar or closely allied composition. Are the extensive masses not simply large-scale equivalents of these satellites, the intrusive mechanism of which has been *proved?* In view of the structural complexity and metamorphosed character of these pre-Cambrian areas, one must be impressed with the large number of instances in which the pre-Cambrian gabbroid masses have been distinctly described as intrusive sheets or laccoliths; and with the other considerable group of cases where the recorded facts point to the same mode of origin.

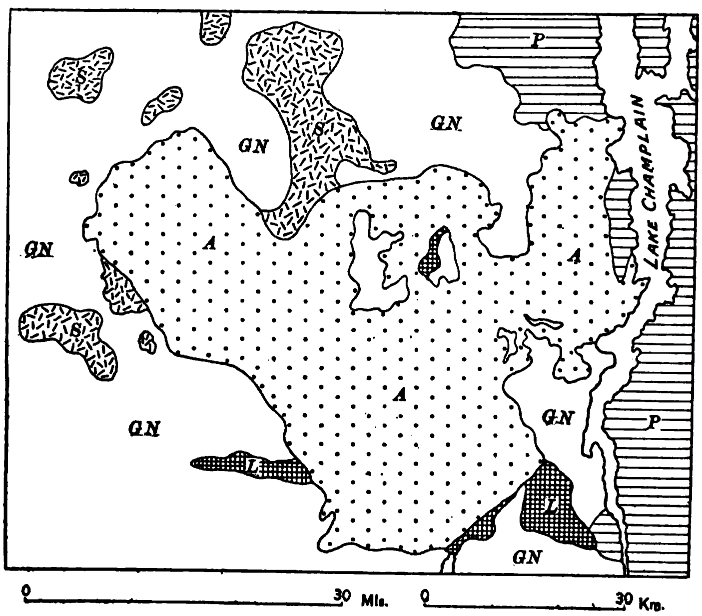

FIG. 157.—Map of anorthosite and syenite in the Adirondacks, New York State. (After the wall-map of the State Survey.) *GN*, gneiss and granite; *L*, Grenville limestone and schists; *A*, anorthosite and gabbro; *S*, syenite; *P*, Cambrian and Silurian sediments (overlap).

Critical field data are lacking for the Saguenay anorthosites (Fig. 156); for the St. Urbain and Moisie River bodies of Quebec; for the many bodies of this rock in the Labrador peninsula, of which about 50,000 square miles, according to Adams's estimate, are covered by anorthosites; for the Adirondack mass (Fig. 157); for the long Newfoundland body; for the anorthosites of Wyoming and Idaho; for the Egersund-Soggendal, Voss-Sogn and Lofoten bodies of Norway; for the Volhynia-Podolia-Cherson anorthosites of Russia; and for the body or bodies in Egypt. Nevertheless, the writer believes it best to entertain the laccolithic hypothesis for all of these and for the other, not listed, smaller bodies of anorthosites and associated gabbros.

Mere size is no barrier to this conception. The greatest known area of anorthosite, the Saguenay mass, is no broader than the Duluth gabbro, to which a laccolithic origin has been ascribed by its latest students. The area of the Saguenay body (5800 square miles) is greater than that of the Duluth body (2400 square miles), but that contrast may be due to the different attitudes of the two masses with respect to the present erosion surface. It is important to note, also, that many well-exposed sills have ground-plan areas of the same order of magnitude. (See page 67.) These well-understood bodies clearly indicate the possibility of horizontal injections characterized by much greater thickness.

Special Conditions for the Formation of Anorthosite.—Yet it seems necessary to postulate unusual conditions for the differentiation of anorthosite from gabbroid (basaltic, substratum) magma.

In the first place, the original magma seems always to have occurred in a very large volume wherever anorthosite is well developed. This is true for all the instances of differentiation in place, as above described. Adams, Kolderup, and others have emphasized the common protoclastic structure in various anorthosites; a feature of the rock indicating a low temperature at the time of the latest magmatic movements, if not at the time of actual injection.[1] It is thus possible that, in these cases, the material of the basaltic substratum was differentiated in depth before the laccoliths were formed. This possibility is matched by the numerous instances where satellitic sheets of pure anorthosite have issued from the larger, visible bodies. But here again, the original gabbroid (basaltic) magma must obviously have had large volumes to supply so great masses of the feldspathic rock by differentiation.

Without attempting the impossible task of evaluating the relative importance of differentiation in place and differentiation in depth, we may conclude that the substratum basalt was erupted into closed chambers during pre-Cambrian time on a scale unmatched in more recent periods. The cause of this contrast evidently furnishes a large question affecting the physical geology of the earth as a whole. The fact suggests speculation as to the existence of a possibly thinner earth crust during the pre-Cambrian and prompts also speculative correlation with the other principal fact that the pre-Cambrian was also a time of the general development of granitic batholiths. These speculations will not be pursued in this place, but it should be noted that the peculiar

[1] F. D. Adams, Ann. Rep. Geol. Surv. Canada, Vol. 8, Pt. J, 1895, p. 115, and elsewhere; C. F. Kolderup, Bergens Museums Aarbog, No. 12, 1903, p. 46.

conditions of later pre-Cambrian time are those allowed for on the hypothesis of a basaltic substratum and on the related assumptions of the eclectic theory here presented.

Rock Types Syngenetic with Anorthosites.—The theory demands that if a large sheet or laccolith of superheated gabbro magma is injected into the earth's crust, some assimilation of roof or floor, or of the walls of feeding dikes, must take place. As detailed in the next chapter, this expectation is abundantly matched by field facts. The question arises as to its bearing on the present connection. Other things being equal, the huge pre-Cambrian laccoliths should show proofs of assimilative power correspondingly greater than that illustrated in the Purcell sills of British Columbia, the Minnesota sills, or the South African sills. (See pages 344, 346, and 349.)

Some of the large masses composed in greater or less part of anorthosite do in fact carry rock phases which are best interpreted as hybrids or else differentiates of syntectic magma. The Duluth gabbro passes not only locally into true anorthosite and also its ultra-femic or ferric complements, but also into the "red rocks," granites, syenites, etc., which have long been correctly referred by N. H. Winchell to solution of country rocks in the gabbro magma. These acid types have been differentiated from the syntectic and are chiefly represented at the roof of the huge intrusion. The case is strictly homologous to that at Pigeon Point, Minnesota, admirably described by Bayley, with whom Winchell, Lawson, and others are in agreement. In Chapters XIX and XX are outlined the reasons underlying the writer's belief that syenites and other alkaline rocks are differentiates of hybrid magmas formed by the solution of basic sediments, etc., in bodies of primary basalt. The anorthosites of the Adirondack Mountains, New York, like those of Norway, are, in fact, intimately associated, and syngenetic with syenitic rocks in appropriate chemical relations to the respective country rocks. In New York, the syenites, with local granitic, monzonitic, and shonkinitic facies, pass gradually, at certain places, into anorthosite and also into the contemporaneous gabbro.[1] At other places the syenite cuts the calcic rocks. The double relation shows the possibility that the more "silicious magma has been first generated in a common chamber with the gabbro-anorthosite and has then been moved intercrustally so as to cut locally the already crystallized femic and calcic rocks." The complex field relations and especially intense deformation and metamorphism have conspired to obscure the exact process by which this assembling of igneous types has been accomplished. Though Cushing believes the Adirondack syenite to have digested anorthosite

[1] H. P. Cushing, Bull. 115, N. Y. State Museum, 1907, pp. 477–479.

at their mutual contact, he also suggests that the syenite is a differentiate of the anorthositic magma.[1]

A close parallel is found in the group of syenitic types, anorthosites, norites, quartz norites, monzonites, adamellites, and banatites in the Ekersund-Soggendal district of Norway. Another likewise found by Kolderup is the consanguineous group of anorthosites, norites, gabbros, mangerites, monzonites, soda-syenites, and soda-granites of the Bergen district and he has also described monzonitic, banatitic, and adamellitic phases in the anorthosite-gabbro area of the Lofoten Islands.[2]

Adams describes contact phases of the Morin anorthosite as charged with quartz and hornblende and notes the sporadic occurrence of orthoclase and biotite. One may suspect here a slight acidification of the original magma, but it seems clear from Adams's account that granitic, syenitic, or other alkaline differentiates of syntectics are here not developed to any notable extent. The same appears to be true for many of the anorthositic areas of Eastern Canada. These failures to show evidence of assimilation may possibly be related to the low temperatures which Adams credits to some of the anorthositic magmas at the time of their intrusion; they were then *not* superheated but were crystallizing, so that solution of foreign material was almost entirely inhibited. The heat supply was, in these cases, just sufficient to permit differentiation of the original substratum material. The cause of this relatively low temperature was perhaps another phenomenon special to the later pre-Cambrian period. But even then, basaltic magma was often superheated at the time of eruption, and that has been the rule for the whole post-Cambrian era.

Conclusions.—The geological facts known about the anorthosites thus appear to sanction the conclusions: (1) that they are gravitative differentiates of basaltic magma of the same composition as that here attributed to the substratum of the earth's crust; (2) that this differentiation generally occurred in large chambers of the laccolithic (or chonolithic) type, though possibly in part below the levels where the visible masses are situated; (3) that the anorthosite bodies, huge as many of them are, are not subjacent or batholithic in character; (4) that the anorthositic laccoliths were developed almost wholly in pre-Cambrian time and that, in general, the world's greatest laccoliths of gabbroid magma were injected during the same period; (5) that some of the anorthositic magmas were generated in chambers hot enough to

[1] H. P. Cushing, Bull. Geol. Soc. Amer., Vol. 10, 1899, p. 188; Bull. 95, N. Y. State Museum, 1905, p. 322.

[2] C. F. Kolderup, Bergens Museums Aarbog, 1896, No. 5; 1903, No. 12; 1898, No. 7.

permit of the solution of large volumes of foreign rock, while others seem not to have been sufficiently superheated to perform notable assimilation; and (6) that no volcanic phase of anorthosite as such has been recognized, though, of course, great laccoliths of basalt may have originated and fed volcanoes above their roofs during the initial, hot, magmatic stage before the anorthositic phase could be differentiated.

Pillow (Ellipsoidal) Basalts and the "Spilitic Suite"

Of late years the "pillowy lavas" have been discovered in many parts of the earth, in terranes ranging in age from the early pre-Cambrian to the twentieth century flows from the Matavanu volcano of Savaii. These lavas are either normal basalts or else types closely allied to them. In most cases their special students have concluded that they represent subaqueous flows. The reason for the balling-up of the lava into relatively small, completely separated pillows or ellipsoids is a physical problem of fascinating difficulty; the structure appears to be connected with the development of the "spheroidal state" at the contact of water and superheated basic lava, but no one has yet made the matter clear.

These pillow lavas have recently won renewed attention since Dewey and Flett stated that "the pillow-lavas are members of a natural family of igneous rocks, the spilitic suite, that can be clearly distinguished from the Atlantic and Pacific suites."[1] Harker himself, the originator of the concept that Atlantic and Pacific suites exist and are related to two different kinds of crustal movements, has acknowledged that "it is at least manifest that the distribution of different groups of igneous rocks in Britain cannot be explained by any initial want of uniformity in the composition of the earth's crust (including the primary magma chamber or chambers) in this tract."[2] According to Harker's hypotheses, the two suites have been differentiated from an originally homogeneous, primordial magma underlying continent and ocean alike, and the cause of that differentiation is found speculatively in the dynamical conditions respectively represented by normal faults and by overthrusts. Several writers have noted reasons for doubting the possibility of distinguishing the two suites, either on a geographical basis or by the types of associated crustal movements. Harker has also admitted that the two suites are petrographically identical at their corresponding acid and basic ends.[3] It is certainly impossible to dis-

[1] H. Dewey and J. S. Flett, Geol. Mag., Vol. 8, 1911, p. 245.

[2] A. Harker, The Natural History of the Igneous Rocks, New York, 1909, p. 109.

[3] A. Harker, op. cit., p. 90.

tinguish many basalts syngenetic with the typical alkaline rocks of Atlantic suites from basalts so often found in Pacific suites. Since the "spilitic suite" is throughout of basaltic habit, it is obviously a difficulty piled on difficulty to distinguish its members from the basic types of the Atlantic suite as distinguished from the Pacific suite and *vice versa*. The offered definition of the new suite thus suffers from the indeterminate nature of the rock classes with which Dewey and Flett have attempted to bring it into contrast.

The independence of the spilitic suite is no more evident if it be compared with the basaltic and diabasic rocks without regard to the assignment of these rocks to the hypothetical suites of Harker, Becke, and Prior. The typical spilites of Germany are most intimately associated with ordinary basalts or diabases and Dewey and Flett admit that all these rocks belong to one eruptive period.[1] The albitic character of the feldspar in spilite is interpreted by those authors as generally not primary but as due to pneumatolytic, "post-volcanic or juvenile changes of rock-masses." They do not discuss the obvious suggestion that the abundant soda of a spilite has been concentrated from an underlying mass of normal basaltic magma; yet there are well-ascertained facts supporting that view. Space here fails for their full presentation but, as usual, special emphasis must be laid on the testimony of the sill, that magmatic form which, when exposed from floor to roof, offers the maximum of certainty as to what actually happens in an eruptive magma. Bowen and Collins have studied instructive examples in Ontario. Many diabase sills of the Nipissing and Timiskaming districts cut Huronian argillites and show albitic facies with veins or dikes of sodic aplite or granophyre. The salic differentiate has tended to accumulate at the roof and its albitic constituent has gone out into the roof argillites, forming typical adinole, essentially like that generated in the slates contacting with the spilites of Europe. These diabases of Ontario are themselves either quite normal or carry small amounts of quartz and micropegmatite. After comparative studies, Bowen concludes that "the literature of albite-rich igneous rocks shows their general association with gabbros intrusive into argillites," and suggests that the "water originally contained in the sediment and, in this class, in large amount, takes an important part in the transfer" of the albite molecule from the normal basaltic magma.[2]

[1] H. Dewey and J. S. Flett, op. cit., p. 205.

[2] W. H. Collins, Econ. Geology, Vol. 5, 1910, p. 538; N. L. Bowen, Jour. Geology, Vol. 18, 1910, p. 658. Similar instances of gaseous transfer and of the development of albite-rich rocks or mineral aggregates by water-gas acting on normal basaltic magma are described by B. K. Emerson (Jour. Geology, Vol.10, 1912, p. 508, and Bull. Geol. Soc. America, Vol. 16, 1905, p. 91) and C. N. Fenner (Annals New York Acad. Sciences, Vol. 20, 1910, p. 93).

The submarine origin of the pillow lavas implies that their magma passed *through* wet sediments of greater or less thickness. Under those conditions water-gas must play an important rôle in modifying the magma in the vents and it seems impossible to doubt that occasionally the upper part of the magma column and also some of the extruded lava will become "albitized." Meanwhile, the general body of the igneous rock must often be profoundly altered by the absorbed water-gas or hot water, exactly as described by the many authors writing of the spilitic masses.

In conclusion, the writer believes that the spilitic rocks are pneumatolytic derivatives of normal basaltic magmas and that the modifying gas is chiefly water of *resurgent*, not juvenile, origin.

Transitions to Other Clans

The eclectic theory requires that there be close field association of basaltic rocks or their chemical equivalent with rocks of all the other clans. This deduction is clearly matched by the facts of distribution for distinct masses, as abundantly illustrated in Table XXI and throughout the pages of this or any other general work on petrology. The intimacy of the associations is again shown in the gradational phases so often observed between basalt, diabase, basic porphyrite, or gabbro, and leading representatives of every one of the other clans. It is not necessary to give complete illustration of this fact, which is known to every informed petrographer. The only doubt possibly arising is that as to the transitions between members of the gabbro clan and members of the alkaline clans. Hence, in Chapter XX this point will be specially noted as one of the indications of a secondary origin for most, if not all, of the so-called alkaline rocks.

CHAPTER XVI

GRANITE CLAN

Included Species

The complexity of the granite problem is indicated by the number of principal species in the granite clan. Again Rosenbusch's hand-book has been used in the preparation of the list of species, though the name "granite" here includes his "granitite." This difference of usage seems to the writer advisable since the biotite-bearing types are by long odds the most abundant rocks of this clan. There is no good practical reason for calling the two-mica species "granite proper." Milch has made the same suggestion, showing that the type "granite proper," as originally distinguished by G. Rose, is merely an altered form of the Riesengebirge biotite granite.[1]

Plutonic Types

A. *Subalkaline Granites.*

1. Muscovite-biotite granite.
2. Lithionite granite, luxullianite.
3. Alaskite, alaskite porphyry, tordrillite.
4. Some biotite granites.
5. Amphibole granite, andengranite, Rapakivi granite.
6. Pyroxene granite, diopside granite, uralite granite, hypersthene granite, enstatite granite, charnockite.
7. Tourmaline granite.

B. *Alkaline Granites (soda granites).*

1. Some biotite granites, some "quartz monzonites."
2. Arfvedsonite granite, ekerite.
3. Riebeckite granite.
4. Hastingsite granite.
5. Aegerite granite.
6. Acmite granite.

Dike Types

A. *Subalkaline Types.*

1. Granite porphyry, alsbachite.
2. Granophyre.

[1] L. Milch, Neues Jahrb. für Miner, etc., B. B. 15, 1902, p. 203; Festschrift zum siebzigsten Geburtstage von Harry Rosenbusch, Stuttgart, 1906, p. 130.

3. Some biotite aplites.
4. Pyroxene aplites, bronzite aplites.
5. Hornblende aplites.
6. Alaskite aplites.
7. Some pegmatites.

B. *Alkaline Types.*

1. Soda granophyre.
2. Ekerite porphyry.
3. Alkaline quartz-syenite porphyry.
4. Some biotite aplites.
5. Paisanite.
6. Some pegmatites.

Effusive Types

A. *Subalkaline Types.*

Rhyolite, liparite, quartz porphyry, some felsites, quartz trachytes, microfelsite, nevadite, microgranite, some granophyres, obsidian, pumice, pitchstone, pitchstone porphyry, felsophyre, vitrophyre.

B. *Alkaline Types.*

Soda rhyolite, soda liparite, krablite, comendite, quartz keratophyre, quartz pantellerite, pantellerite.

General Statement

The eclectic theory assumes, for the reasons assigned in Chapter VIII, that granitic material composed the outermost original shell of the earth. The thin, rhyolitic, scoriaceous, surface skin theoretically expected would obviously be an ephemeral feature in the primitive areas subject to moderate erosion. Beneath this phase the material would be granitic in texture as well as in chemical composition. Of late years some geologists have been accustomed to deny the existence of any remnant of a primitive crust among the visible terranes. This conclusion is hazardous, since it is based on an induction which cannot be regarded as complete until all the pre-Cambrian formations have been examined in detail. Many generations of geologists will be required before these rocks are well mapped and their structural relations determined with sufficient certainty to allow of final belief in the complete invisibility of the primitive crust. That its remnants must cover but small areas is now practically certain; but no one can yet be sure that some of the granitic rocks already discovered are not parts of that primitive crust, which has remained unfused since the day of its original consolidation. The question remains still insistent for those geologists who, for example, are working in the basement complexes of Fennoscandia and Canada.

On the other hand, the vast majority of the rocks referable to the granite clan are definitely eruptive. The problem of their origin is so broad in its scope that it may almost be regarded as equivalent to the petrogenic problem as a whole. The eclectic theory stands or falls according to its ability not only to explain these eruptives but also to forecast future discoveries concerning the granites and their allies. Obviously, neither of these tests can yet be applied in detail. An extremely great development of the theory is still necessary before the exact conditions under which a pyroxene granite rather than a biotite granite, or a comendite rather than an ordinary rhyolite,has formed at a given place. Only a few of the more salient points on the genesis of these granitic and allied eruptives can now be discussed with profit. Some of these have been selected as affording illustrations of the more important principles bearing on the granite problem.

The origin of post-Keewatin granitic magma in general has already been discussed in Chapters VI, VIII, X, XI, and XII. In general it is primitive material of the earth's crust which has separated from syntectics, periodically and locally formed between primary basalt and the primary acid earth-shell. The silicious differentiate has largely crystallized in batholiths and stocks, which have no visible floors. It is, therefore, supremely important that true granites have been found in the appropriate relation to the basaltic magma of thick sheets with exposed floors and roofs. In the visible rocks of such injections all transitions between pure basaltic (gabbroid) magma into the syntectic and thence into its typical granitic differentiate, are represented. Though the known number of thick sills and allied intrusive sheets of basic magma is small, their magmatic behavior merits special attention. Each of them in its results is like a gigantic experiment in petrogenesis; each well-exposed chamber is a crucible which can be examined from top to bottom. The batholith or stock can be examined only at levels near its roof and, therefore, obviously fails in every case to furnish all the data required in the granite problem. For this reason the writer has laid particular stress on those basic sheets in which granites have been differentiated.[1] In his opinion they should be given right of way in a discussion of granites in general. The reader is referred for details to the writings listed in the accompanying footnote, but an abstract of the essential facts there described, together with important additional illustrations, will be useful.

[1] R. A. Daly, Memoir No. 38, Geol. Surv., Canada, 1912, pp. 221–255; Amer. Jour. Science, Vol. 20, 1905, pp. 185–216; Festschrift zum siebzigsten Geburtstage von Harry Rosenbusch, Stuttgart, 1906, pp. 203–233.

Species Derived from Syntectics of Sediments and Basaltic (Gabbroid) Magma

Purcell Sills.—Among the best-exposed examples are the Purcell sills, which cut Cambrian or older sediments in southeastern British Columbia. Those studied in greatest detail form a group invading

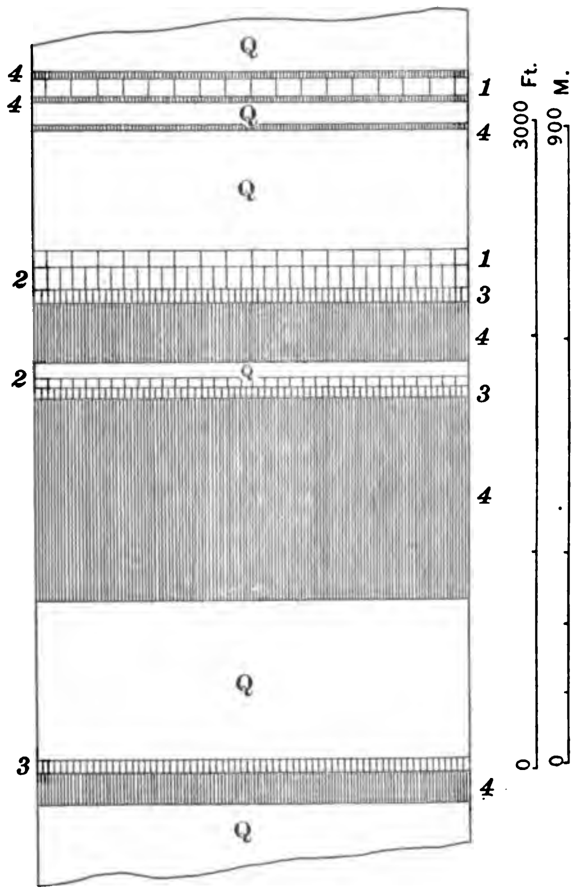

Fig. 158.—Section, to scale, of the differentiated sills at the Moyie River, British Columbia. (R. A. Daly, Memoir 38, Geol. Surv. Canada, 1912, p. 248.) Q, quartzite; *1*, biotite granite; *2*, hornblende-biotite granite; *3*, intermediate rock; *4*, gabbro. Five sills shown.

very thick, homogeneous, feldspathic and micaceous quartzites at the point where the Moyie river crosses the International Boundary. The thickness of these bodies varies from 100 feet or less to about 1500 feet. They illustrate gravitative differentiation with perfect clearness (Fig. 158). In each of several instances the sheet consists at the top of a true biotite granite (rarely hornblendic) passing downward into hornblende gabbro. Especially at the upper contact of one of the thicker sills the quartzite is more or less intensely metamorphosed. While preserving its bedding, the now massive sediment has a field habit and microscopic character markedly like those of the sill granites. In both rocks micropegmatite is abundantly generated. The field impression that the granitic layers are due to the assimilation of the quartzites is corroborated by chemical analysis.

Similar cases discovered further north in the Purcell mountain system are reported by Schofield and, in the present writer's opinion, the granitic phases there are differentiates from the same type of quartzite-gabbro syntectics.[1] South of the International Boundary, Calkins found still other examples and has briefly described two of the gravitatively differentiated sills. He is of opinion that here also the materials differentiated were syntectics of basic magma and silicious sediments.[2]

In these sills of the Purcell mountains occasional quartzitic inclusions are seen to be surrounded with shells of mixed material which can only be interpreted as the actual syntectic. Such material was evidently "frozen in" before it could rise away from the xenolith, itself enclosed in the magma when the viscosity was very great. In the earlier, hotter state of the magma the dissolved silicious matter diffused into the original gabbroid melt and, when the magmatic state was sufficiently prolonged, largely collected at the top of the sill. If, on the other hand, the sill was thin and cooled with relative quickness, this secondary magma remained diffused through the original gabbro and there crystallized. Such appears to be the best explanation of the abundant interstitial micropegmatite and quartz found by the writer and by Schofield, Calkins, MacDonald, and Pardee in the numerous sills and dikes of this extensive region.[3]

A chief ground for belief that these acid phases originated in assimilation is found in the "consanguinity" between the somewhat abnormal granite and the invaded sediments. The relative homogeneity of the latter through thousands of feet of thickness permits a fairly close estimate of their average chemical composition. This principal datum is very seldom afforded in areas containing thick basic sills; hence special emphasis must be laid on the facts determined in the Purcell mountains.

The field evidence is clear that the assimilation was not confined to the sill chambers actually occupied by the secondary granite. The

[1] Cf. S. J. Schofield, Summary Rept., Geol. Survey of Canada for 1910, p. 131.

[2] F. C. Calkins, Bull. 384, U. S. Geol. Survey, 1909, pp. 48–50.

[3] Cf. J. T. Pardee, Bull. 470, U. S. Geol. Survey, 1911, p. 47.

solution of quartzite at their main contacts and of sedimentary blocks stoped down or up from those contacts has unquestionably taken place; but it is highly probable that assimilation occurred during the upward passage of the gabbroid magma through the sediments underlying each of the thicker sheets. Apophysal dikes are occasionally sent off from the granitic upper layers. It is reasonable to believe that, after the differentiation of these layers, their acid magma (secondary granite) would sometimes be injected, as sills, into the overlying sediments. Such intrusions, late in the history of the magmas, would theoretically be aided by the great tension of the resurgent gases. Such is one explanation which has been offered for a few of the purely granitic sills found in the Purcell mountains.[1]

Marysville Sill.—In the Marysville mining district of Montana the shales and sandstones of the Belt series are cut by thin and thick sills of gabbro. This rock seems to be generally of normal composition but at the roof of one of the sheets the intrusive is a muscovitic micro-granite, carrying 40 per cent. of quartz and 40 per cent. of alkaline feldspar. The dense granite is nearly of the same color as the overlying hornstone, which is itself a quartz-muscovite rock, yet the silicious phase of the sheet encloses "many small, sharp chips of the hornstone." The evident chemical and mineralogical similarity between granite and hornstone and the geological relations of each to the normal gabbro strongly suggest that we have here a homology to the Moyie sills.[2]

Minnesota Cases.—The well-known sheet or dike at Pigeon Point, Minnesota, is another striking parallel (Figs. 149 and 159). At its hanging wall the gabbro is overlain by true granite, which Bayley, basing his conclusion on unusually thorough field, chemical, and microscopic study, has interpreted as due to the solution of slate and quartzite in the original gabbroid magma. After independent field study, Lawson states his full agreement with this conclusion.[3]

Similar relations obtain in the Duluth laccolith; its maximum thickness is to be measured in miles (Fig. 149). The laccolith cuts Upper Huronian slates and more acid sediments, as well as the Lower Huronian and pre-Huronian complex. Along its upper contact are huge masses of "red rocks," granites, syenites, etc., which have long been explained by Norwood and N. H. Winchell as products of the

[1] R. A. Daly, Memoir No. 38, Geol. Survey of Canada, 1912, p. 249. This memoir contains a detailed discussion of the Purcell sills.

[2] J. Barrell, Prof. Paper 57, U. S. Geol. Survey, 1907, p. 48.

[3] W. S. Bayley, Bull. 109, U. S. Geol. Survey, 1893. A. C. Lawson, Bull. 8, Geol. and Nat. Hist. Survey, Minnesota, 1893, pp. 30, 31, 44.

solution of the sediments by the gabbroid magma.[1] The lavas overlying the "red rocks" are closely allied to the laccolithic rocks.[2]

The Bad River laccolith of Wisconsin is 60 miles long and for most of its length is from 2 to 5 miles wide (Fig. 151). The maximum thickness has been estimated at 25,000 feet.[3] Along the roof is a long outcrop of acidic "red rock," which resembles the secondary granite of the Pigeon Point intrusive. Van Hise and Leith regard this "red rock" of the Bad River laccolith as a dike cutting the gabbro, but the relation of the two types is suspiciously like that in the Pigeon Point, Sudbury,

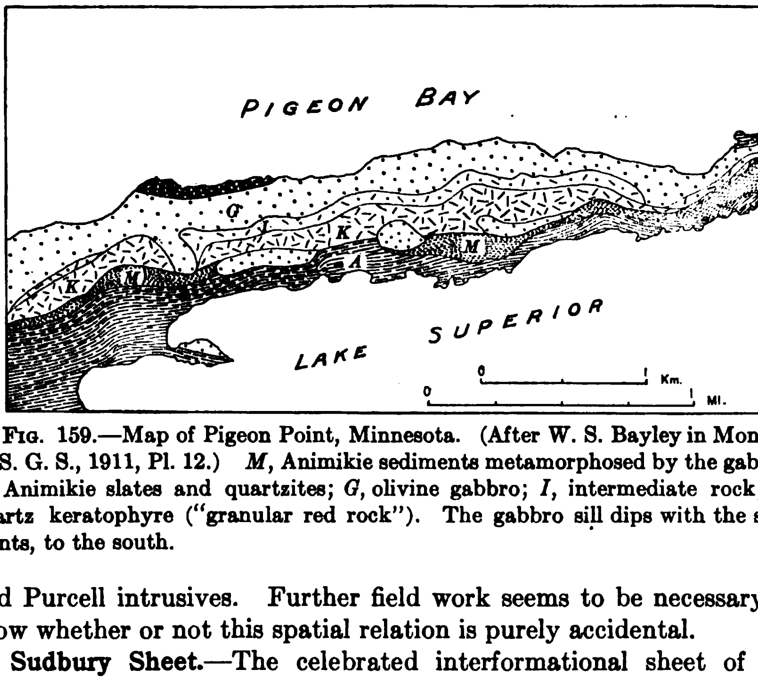

FIG. 159.—Map of Pigeon Point, Minnesota. (After W. S. Bayley in Mon. 52, U. S. G. S., 1911, Pl. 12.) *M*, Animikie sediments metamorphosed by the gabbro; *A*, Animikie slates and quartzites; *G*, olivine gabbro; *I*, intermediate rock; *K*, quartz keratophyre ("granular red rock"). The gabbro sill dips with the sediments, to the south.

and Purcell intrusives. Further field work seems to be necessary to show whether or not this spatial relation is purely accidental.

Sudbury Sheet.—The celebrated interformational sheet of the Sudbury district furnishes a standard case of gravitative differentiation, with granite and granodiorite (micropegmatite) passing downward, through intermediate rock, to norite at the lower part of the intrusive. During a visit to the field the writer was impressed with the great resemblance of this body to the differentiated sills of the Purcell moun-

[1] N. H. Winchell, Final Report, Geol. and Nat. Hist. Survey, Minnesota, Vol. 5, 1900, p. 978.

[2] See Monograph 52, U. S. Geol. Survey, 1911, pp. 202 and 377, and large map in pocket; also Final Report, Geol. and Nat. Hist. Survey, Minnesota, Vol. 4, 1899, plates 66, 67, 68, 69.

[3] C. R. Van Hise and C. K. Leith, Monograph 52, U. S. Geol. Survey, 1911, p. 377, and large map in pocket; see also plate 22 in R. D. Irving's "Copper-bearing Rocks of Lake Superior," Mon. 5, U. S. Geol. Survey, 1883.

tains; and with the likeness of general field habit between the Sudbury micropegmatite and the overlying, intensely metamorphosed sediments. Coleman has, in fact, found field evidence of the stoping and digestion of quartzite blocks in the noritic magma.[1] Here, again, it would seem probable that all of the assimilation of acid rocks is not to be credited to the original magma *after* injection; some of it may have been accomplished during the injection of that magma through the underlying quartzitic and "Laurentian" terranes (Figs. 160 and 161).

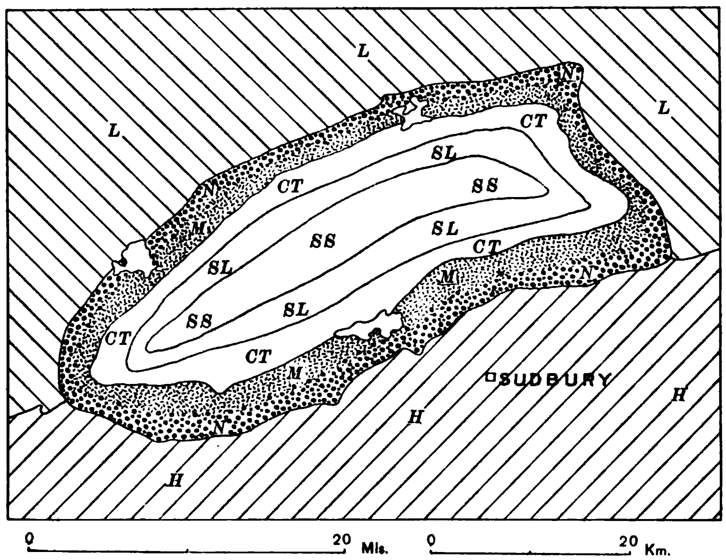

FIG. 160.—Map of the Sudbury district, showing nickel-bearing interformational sheet. (After A. P. Coleman, Rep. Bur. Mines, Ontario, Vol. 14, 1905.) *L*, Laurentian gneiss and granite; *H*, lower Huronian slate, quartzite, graywacke, greenstone, etc.; *CT*, Trout Lake conglomerate and Onaping tuff; *SL*, Onwatin slate; *SS*, Chelmsford sandstone; *N*, norite; *M*, micropegmatitic granite and granodiorite. The sheet has a basin structure.

It should be noted that the outcrop areas of the rocks cannot be assumed to show the exact ratio of volumes between acid and basic types in this sheet. Coleman holds that it was warped into a spoon shape during or immediately after intrusion. If such is the case, the acid differentiate should have collected in greatest thickness on the outer, upper rim of the "spoon." The initial superheat of the basic magma need not, therefore, be assumed to be so great as that demanded if assimilation had taken place in proportion to the average widths of the actual outcrops of granite and norite.

Many other bodies, illustrating the common development of micro-

[1] A. P. Coleman, Jour. Geology, Vol. 15, 1907, pp. 774 and 778.

pegmatite, either disseminated or segregated, in intrusive diabase, gabbro, or norite cutting acid rocks, have been found in Minnesota, Ontario, Quebec, Connecticut, Scotland, Sweden, Finland, Russia, India, South Africa, Australia, Antarctica, etc. In some of these, gravity has clearly controlled the segregation of the granitic magma or its analogue. A few of such additional cases may be mentioned.

Insizwa Intrusion.—A notable parallel to the Sudbury sheet is furnished by the great Insizwa intrusion of East Griqualand.[1] It is a sheet 2000 or 3000 feet thick, intrusive into the shales and sandstones of the Beaufort series (Karroo system). The dominant igneous types are gabbro and norite, which merge into each other. At the bottom is

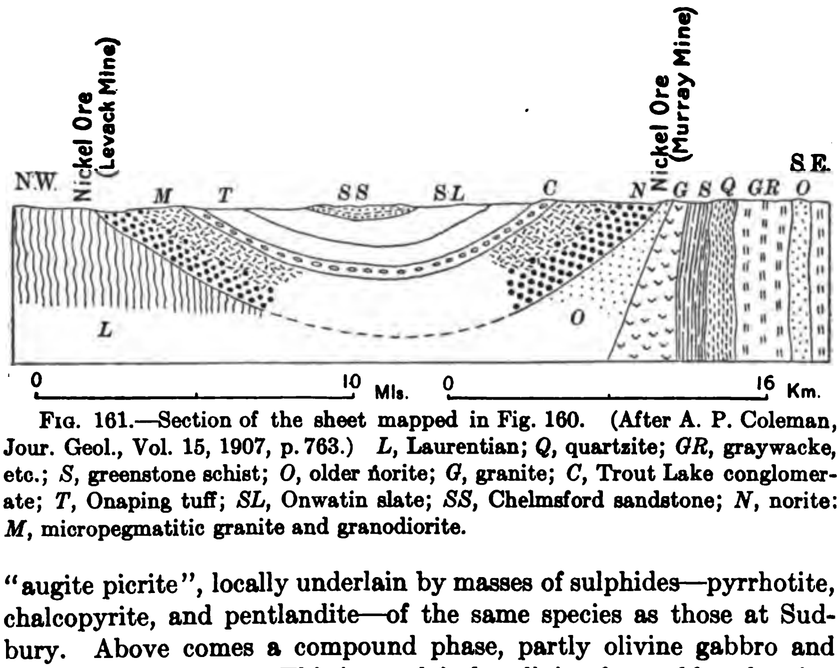

FIG. 161.—Section of the sheet mapped in Fig. 160. (After A. P. Coleman, Jour. Geol., Vol. 15, 1907, p. 763.) *L*, Laurentian; *Q*, quartzite; *GR*, graywacke, etc.; *S*, greenstone schist; *O*, older norite; *G*, granite; *C*, Trout Lake conglomerate; *T*, Onaping tuff; *SL*, Onwatin slate; *SS*, Chelmsford sandstone; *N*, norite: *M*, micropegmatitic granite and granodiorite.

"augite picrite", locally underlain by masses of sulphides—pyrrhotite, chalcopyrite, and pentlandite—of the same species as those at Sudbury. Above comes a compound phase, partly olivine gabbro and partly olivine norite. This is overlain by olivine-free gabbro, bearing much interstitial micropegmatite and cut by veins of coarse pegmatite. Both gabbro and adjacent hornfels are cut by small dikes of "micro-granite." The sediments are intensely metamorphosed for a distance of more than 400 feet from the upper contact and for a distance of 200 feet from the lower contact. No individualized layer of micropegmatite or granite appears at the upper contact, as at Sudbury. For some reason, perhaps for lack of sufficient superheat, this South African magma has not digested the acid sediments to the same degree as that manifested in the Ontario, Minnesota, and British Columbia cases.

[1] A. L. du Toit, 15th Ann. Rep. Geol. Comm., Cape of Good Hope, 1910, p. 111.

Other South African Cases.—The thick intrusive sheets of diabase or dolerite, cutting the Pretoria shales and quartzitic sandstones, are known to contain acid ("felsitic") micropegmatitic phases which merge into the basic rock, but details of their precise structural relations are yet lacking.[1] Hatch and Corstorphine state that this micropegmatitic type has "much resemblance to, and is perhaps genetically connected with, the 'red granite'" of the district. Mellor has described this red granite as forming the roof phases of laccoliths which are not exposed to depth sufficient to show floors or their own lower levels.[2]

Rogers and du Toit remark on the abundance of small veins and masses of quartz-orthoclase rock in the rock of the numerous dolerite sheets of the Karroo; and state that it is difficult to distinguish this acid rock from the (metamorphosed) sediments cut by the sheets.[3] From the Natal dolerites Prior has described a "hybrid rock" collected by Anderson who labelled it "basalt which has absorbed granite"; its essential constituents include biotite, augite, and micropegmatite.[4] Prior regards the effusive rhyolites of the Lebombo Range in the Natal-Zululand doleritic region, as well as the granophyres of the intrusive bodies, as probably differentiation products "of the same magma which supplied the dolerites." There is thus something to be said for the view that the acid rocks, both intrusive and volcanic, associated with dolerites in the vast South African field, are of secondary origin.

But the most remarkable intrusive body in South Africa is the Bushveldt laccolith of the Transvaal (Fig. 162). It is 250 miles in length and 75 miles in width. It is composed of red, micropegmatitic or granophyric granite, gabbro, norite, pyroxenite, and iron-chromium ores. The ores and ultra-femic rocks and ores occur at the floor contact, the granite at the roof, and the norite-gabbro phases in an intermediate position. Their arrangement is strictly analogous to that shown in the Sudbury sheet and there can be little doubt that gravity has controlled the differentiation of this Transvaal intrusion, the largest laccolith yet described by critical and competent geologists.[5] No direct evidence as to the original nature of the differentiated magma

[1] F. H. Hatch and G. S. Corstorphine, The Geology of South Africa, London, 1905, p. 172.

[2] E. T. Mellor, Trans. Geol. Soc. South Africa, Vol. 7, 1904, p. 45.

[3] A. W. Rogers and A. L. du Toit, 13th Ann. Rep. Geol. Comm., Cape of Good Hope, 1908, p. 105. Cf. A. W. Rogers, 15th Ann. Report of same, 1910, p. 9; A. L. du Toit, 16th Ann. Rep., 1912, p. 102.

[4] G. T. Prior, Annals, Natal Museum, Vol. 2, 1910, p. 150.

[5] G. A. F. Molengraaff, Bull. soc. géol. France, Vol. 1, 1901, p. 13; Geology of the Transvaal, Johannesburg, 1904, p. 49. H. A. Brouwer, Oorsprong en Samenstelling der Transvaalsche Nephelien-syenieten, 's Gravenhage, 1910, p. 9. These unusually valuable memoirs illustrate the richness of the South African field in the speaking facts of igneous geology.

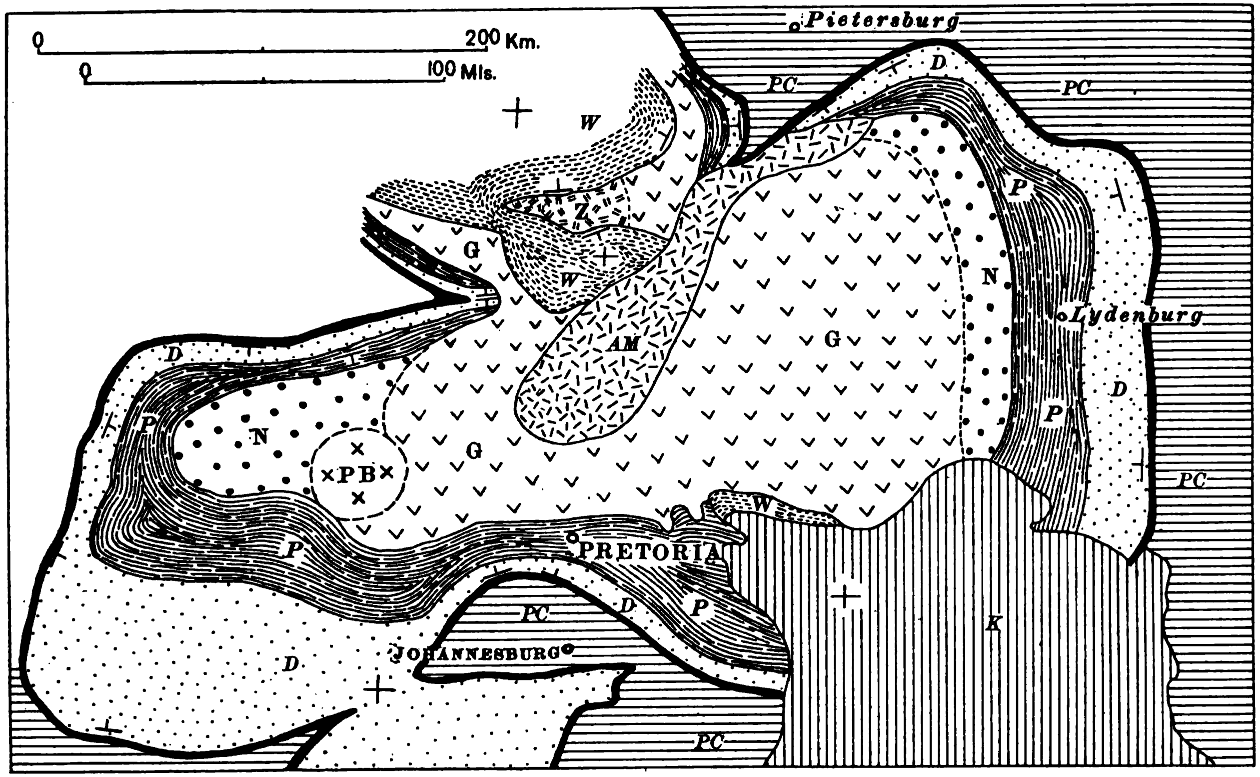

FIG. 162.—Map of the Bushveldt laccolith, Transvaal. (After G. A. F. Molengraaff, Bull. Soc. géol. France, Vol. 1, 1901, Pl. 1; and H. A. Brouwer, 1910.) *PC*, pre-Cape complex; *solid black*, Black Reef series; *D*, Great Dolomite; *P*, Pretoria series; *W*, Waterberg sandstone; *N*, norite, pyroxenite, with iron ore; *G*, red granite; *PB*, nephelite syenites of the Pilandsberg; *Z*, porphyries of the Zwagershoek; *AM*, amygdaloid; *K*, Karroo sediments, etc. Symbols for strike and dip.

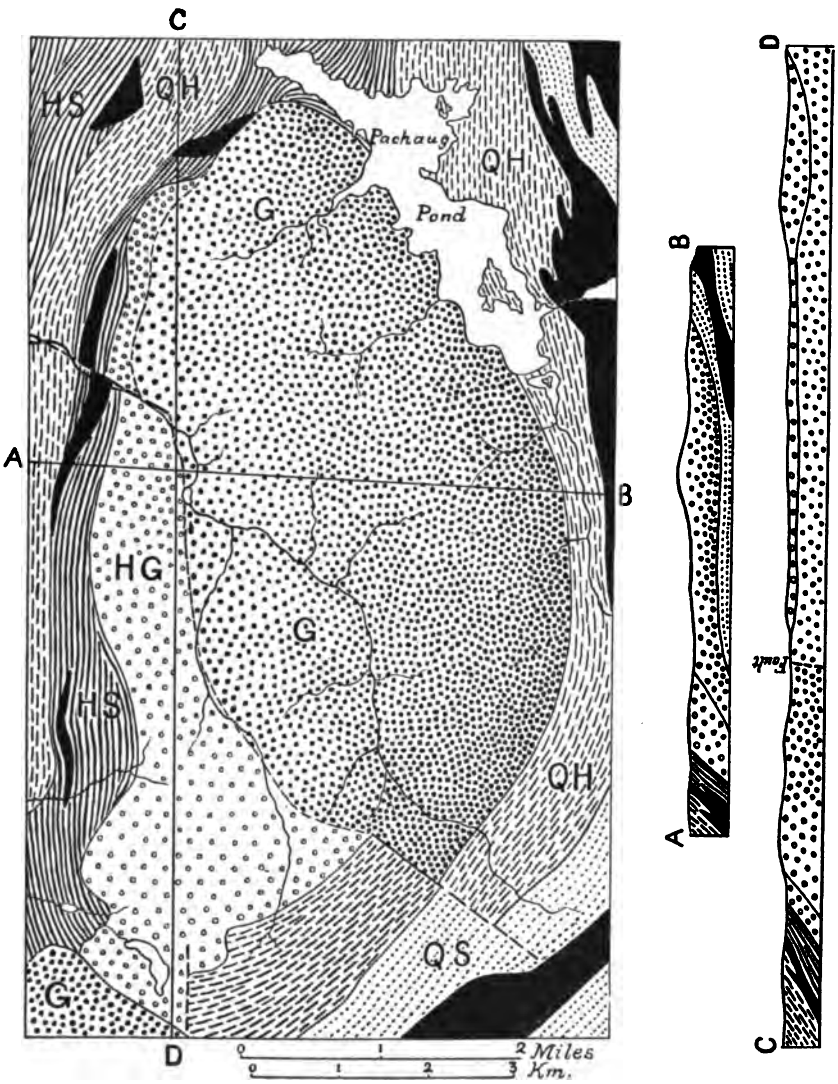

FIG. 163.—Map and sections (*AB* and *CD*) of the gabbro laccolith at Preston, Connecticut. (After G. F. Loughlin, Bull. 492, U. S. G. S., 1912.) *QS*, quartz schist; *QH*, quartz and hornblende schists; *HS*, hornblende schist; *solid black*, Sterling granite gneiss; *G*, gabbro; *HG*, quartz-hornblende gabbro. *G* and *HG* are phases of the same laccolith; general decrease of density, from the floor upward, shown by varying closeness of dots.

has been published but the detailed similarities to the intrusive sheets and laccoliths of British Columbia, Minnesota, etc., warrant the hypothesis that the original magma was gabbroid, modified by the solution of the intruded acid rocks. The assimilation in this case may have been largely accomplished at levels below the horizon of intrusion (base of the Waterberg system of sediments).

Preston Laccolith.—The Preston gabbro of Connecticut is described as a laccolith outcropping in an area measuring 3.5 miles by 6 miles (Fig. 163). It has a low dip to the west and both roof and floor phases are exposed. The body cuts quartzites and acid, sedimentary schists. The lower and greater part of the intrusive is an ordinary diallage gabbro; the capping phase is a quartz-hornblende gabbro, carrying accessory biotite (2–5 per cent.), with andesine accompanying labradorite. The quartz often occurs in micropegmatitic intergrowths. The two phases grade into each other and the quartz-hornblende gabbro locally grades into an oligoclase granite, which forms segregations as well as dikes cutting the more acid, main phase. Other, smaller gabbro bodies in the vicinity likewise show free quartz at their upper contacts. Loughlin explains the relations by gravitative differentiation but offers no suggestion as to the cause of the abnormal composition of the gabbro as a whole. The hypothesis that assimilation of the country rocks was responsible should be entertained.[1]

Medford Dike.—Many cases of obvious assimilation (corrosion) of quartzose xenoliths by diabasic or basaltic magma have been recorded. Jaggar has made a detailed study of the marked corrosion of quartz and quartzite xenoliths as exerted by the magma of the wide Medford dike of diabase at Boston, Massachusetts. The mineralogical effects are here special but again the interaction of magma and inclusion has led to the crystallization of a micropegmatite composed of quartz and microcline. The dike also contains irregular lenses of quartz-microcline pegmatite which merges gradually into the normal diabase. The facts presented by Jaggar show that there has not been merely a solution of acid foreign rock *in situ;* on the other hand, it is clear that the corrosion aureoles and the pegmatites have attained their composition through a kind of osmotic transfer aided by the gaseous constituents. Thus even here differentiation has tended to mask the proofs of assimilation, yet the fact of corrosion is evident. It is further important to note that the rock of this dike, while generally a normal diabase, has a (basic) hornblende-augite diorite phase and a hornblende-biotite diorite phase, suggesting analogous local changes in the original magma.[2]

[1] G. F. Loughlin, Bull. 492, U. S. Geol. Survey, 1912, p. 78.
[2] T. A. Jaggar, Amer. Geol., Vol. 21, 1898, p. 203.

Globe District Intrusions.—The intrusive diabase of the Globe district, Arizona, contains quartzose inclusions which are "conspicuously corroded and embayed."[1] The diabase forms thick sills, chonoliths, and dikes cutting Paleozoic and older quartzites, thick limestone, grit, conglomerate, and acid and basic schists. The differentiate of the average syntectic in this instance should not be expected to be a highly quartzose rock or granite. As a matter of fact, the *larger* diabase masses carry true syenitic phases interpreted in the field as local facies of the diabasic magma.[2]

Swedish Cases.—"In the southernmost part of Sweden one Jotnian area only occurs, the so-called 'Almesåkra group,' S. E. from the southern end of Lake Wettern. This group is composed of white and red quartzites, felspar-bearing sandstones and arkoses, chocolate-brown shales and, more subordinately, conglomeratic layers and red calcareous sandstones. Dikes and beds of diabase are very abundant. They are remarkable by the intense contact influence exercised on the quartz-rocks, many times resulting in micrographic quartz-diabases and other rock-varieties of abnormal composition, as is described by Hedström. Fragments of the intruded rocks have also been more or less affected by the diabase magma."[3]

Högbom describes modifications of olivine diabase intruded, as sills, etc., into sandstone and granite in Ångermanland. Near its contacts the diabase loses its olivine and becomes a quartz diabase with well-developed micrographic structure. Hybrid rocks are produced at the contact of the diabase and the older granite and veins of granite (red in color as usual in these circumstances) cutting the diabase are interpreted by Högbom as salic segregations of the acidified diabase.[4]

Scottish Intrusions.—G. W. Tyrrell describes laccoliths and feeding dikes of quartz diabases in the Kilsyth-Croy district of Scotland and suggests that these rocks, like micropegmatitic diabases and gabbros in general, "owe their origin to the interaction of a normal basalt-magma with a highly silicious country rock." He further notes that "the mode of occurence of this rock (micropegmatitic diabase or gabbro) is also distinctive. It always occurs in thick massive, vertical-sided dikes, which sometimes continue for many score miles across country, and also as thick laccolitic protrusions from such

[1] F. L. Ransome, Globe Folio, U. S. Geol. Survey, 1904, p. 8.

[2] F. L. Ransome, Prof. Paper 12, U. S. Geol. Survey, 1903, p. 85. See page 395 of the present book.

[3] A. G. Högbom, Bull. Geol. Inst., Upsala, Vol. 10, 1909, p. 9; cf. H. Hedström, Blad 5, Ser. Ala, med Beskrifning, Sveriges Geol. Unders., 1906.

[4] A. G. Högbom, Geol. Fören. Stockholm Förh., Vol. 31, 1909, pp. 369–370.

dykes."[1] Tyrrell's generalization as to the large size of each of these intrusive bodies is one also forced on the present writer as a result of compiling the geological literature, and it must be regarded as full of meaning for the petrogenic problem. Only in the larger injections of basaltic magma should notable amounts of silicious country rocks be absorbed.

Stecher had long before stated the probability that the quartz diabases of the Firth of Forth region owe their free silica to solution of acid country rocks in normal diabase. He described the corrosion of quartzose inclusions and quotes A. Geikie's statement of belief, founded on field evidence, that solution of silicious xenoliths actually took place in these intrusive bodies. Stecher further notes Schröder's conclusion that diabase has dissolved granitic material in the area covered by the Falkenberg sheet of the Saxon Geological Survey.[2]

Intrusions of British Guiana.—British Guiana has notable illustrations of syngenetic diabase and granophyre. The dominant diabase occurs in dikes, thick sills, and "laccoliths," cutting very thick sandstones and conglomerates. It is generally normal in type (specific gravity 2.93–3.17), but is in places transitional into micropegmatitic diabase and true augite granophyre (sp. gr. 2.93–2.77). Free quartz, microcline, and biotite, are developed. The "laccolith" at Mount Roraima is about 2000 feet thick.[3] The types and conditions of intrusion are much like those in the other extensive fields already noted. Although Harrison expressed no opinion as to origins, it seems necessary to postulate the same mode of formation for the different igneous types. Harrison notes the rarity of olivine diabase in the British Guiana bodies, a fact finding ready explanation if the primary basaltic magma was here even slightly acidified by the solution of sandstone.

SPECIES DERIVED FROM THE SYNTEXIS OF NON-SEDIMENTARY, ACID ROCKS.

In nearly all of the cases so far cited the granitic differentiate is found in basic injections cutting acid sediments. Several authors have independently suggested that the acid rock is ultimately due to assimilation of the sediments. The solution and differentiation are both aided by the presence of water in the intruded formations.

On the other hand, Gavelin has recently described "magnificent

[1] G. W. Tyrrell, Geol. Mag., Vol. 6, 1909, pp. 363–365.

[2] E. Stecher, Tschermak's Min. und Petr. Mitt., Vol. 9, 1888, p. 193.

[3] J. B. Harrison, Geology of the Goldfields of British Guiana, London, 1909, pp. 22, 24, 92.

remelting and assimilation phenomena" at the contact of gabbro cutting the Loftahammar granite of Sweden. Quartz gabbro, diorite, and regenerated micropegmatitic granite have been there developed.[1] One is reminded of the intimate association of granitic and diabasic magmas in the great Brefven dike, south of Lake Hjälmaren, Sweden, which cuts acid crystalline rocks (Fig. 24).[2] Mennell has found convincing evidence that the material of the Matopo granite was dissolved in the wide, doleritic dikes of Rhodesia. This author speaks of "splendid examples" of the melting of granite by the dolerite, and of there being "every gradation" between the granophyres of the region and an "obvious mixed rock." He suggests that, in general, the common association of granophyre with gabbro or dolerite is due to "admixture of acid and basic materials before intrusion," a deduction very similar to that reached by the present writer in the study of the Moyie sills.[3] Moberg described the development of micropegmatite, biotite, and orthoclase in the olivine diabase of the Blekinge district, Sweden, and explained this modification of the diabase by the absorption of the country rock, gneiss.[4]

Syntexis in Feeders of Fissure Eruptions

The feeding channels for great fissure eruptions are characteristically narrow but each of their walls must have become intensely heated during the passage of large volumes of the erupted basalt. The dike material left in the fissure should, therefore, show some evidence of contact assimilation. In the writer's belief this expectation is matched by the discovery of abundant free quartz and micropegmatite in the dikes (and associated gabbro sheets) which fed the Eocene fissure eruptions of basalt in Central Washington. Solution of the sandstone or otherwise acid walls of the feeding channels may also be responsible for the quartz basalt, exceptionally found in the Eocene (Teanaway) extrusive sheets of this region[5] (Fig. 70). The feeders of the Cuddapah trap flows, in southeastern India, are likewise

[1] A. Gavelin, Geol. Fören. Stockholm, Förh., 1910, p. 999.

[2] P. J. Holmquist, Bull. Geol. Inst., Univ. Upsala, Vol. 7, 1906, p. 107; A. G. Högbom, Sveriges Geol. Unders., Ser. C. No. 182, 1899, p. 11, and Bull. Geol. Inst. of Upsala, Vol. 10, 1910, p. 18; K. Winge, Geol. Fören. Stockholm, Förh., Vol. 18, 1896, p. 187.

[3] J. P. Mennell, Geol. Mag., Vol. 8, 1911, p. 10; Quart. Jour. Geol. Soc., Vol. 66, 1910, p. 372; Cf. Amer. Jour. Science, Vol. 20, 1905, p. 215.

[4] See reference in Rosenbusch's hand-book, 4th ed., 1908, p. 1250.

[5] G. O. Smith, Mount Stuart folio, 1904, and G. O. Smith and F. C. Calkins, Snoqualmie folio, 1906, U. S. Geol. Survey.

more acid than the extrusive traps and vary from norite, through diorite, to micropegmatitic granite.[1]

In both these great fields, many, if not most, of the masses of extrusive basalts are normal. They do not carry free quartz or micropegmatite, nor are they more silicious than the average basalt of the world. Since this common magmatic type is interleaved with the more exceptional quartzose type, and since both types were erupted by the same mechanism, in the same region and in the same geological period, it seems in the highest degree improbable that the quartz-bearing or more silicious basalts can represent a primary magma independent of the normal basalt. Between quartz diabases and normal diabase, and between quartz gabbro and normal gabbro, there are very often recorded the closest associations, in structural relations, in mode of eruption, and in time of eruption. Here again must be felt the great difficulty of crediting an independent origin for the respective rock species.

Conclusions.—Without further multiplying illustrations, it is clear that the phenomena of the larger injected masses, especially sills, are of great value in any genetic theory of the granites. In each of several large fields, where basaltic (gabbroid or diabasic) sheets have been thrust into sediments, the thinner sheets and associated dikes preserve throughout their original composition; while the thicker sheets roughly, though far from absolutely, in proportion to their thickness, have been chemically modified. This modification is always in the direction toward a syntectic with the country rock—generally quartzose sediments. As a rule, quartz diabases (Konga-diabase type, etc.), quartz gabbros, or quartz norites, are developed. Only occasionally has the sheet been large enough, that is, liquid for a sufficient period, to permit of marked differentiation of these syntectics. Then granitic layers are formed at the roofs of the magmatic chamber. The differentiates are seldom or never precisely equivalent, in chemical composition, to the average sediment assimilated; yet there is often an unmistakable "blood relationship" between the igneous and stratified rock. No other process than assimilation seems capable of explaining this consanguinity and many field evidences positively favor this explanation. Further, gravitative differentiation is obvious in the larger sheets. Hence, in the writer's opinion the eclectic theory is

[1] T. H. Holland, Quart. Jour. Geol. Soc., Vol. 53, 1897, p. 405. Fermor states that the rhyolitic lavas, locally found in the Deccan traps, are consanguineous with the dominant basalt, regarding the two types as differentiates of the same magma (L. L. Fermor, Records, Geol. Survey, India, Vol. 34, 1906, p. 148). Was this magma a syntectic of primary basalt and acid crystalline rock such as forms the walls of the feeding dikes?

well matched by the facts of nature in the case of the only natural bodies which can be examined *fully*, from top to bottom.

Transitions to Batholiths

Most of the instances of the differentiation of acid magmas from basaltic syntectics have been selected from the list of sheet injections which illustrate the phenomena. It is obvious that the same processes should control originally superheated basaltic magma in the case also where it is intruded as a wide dike into silicious rocks. However, we have already seen that very wide dikes are rare. Except where dikes are the feeders of fissure eruptions, or of great laccoliths or sheets, they must speedily be chilled to temperatures too low for significant assimilation. This seems to be a leading reason why dike diabases, gabbros, porphyrites, etc., so seldom show direct evidence of acidification by the solution of wall rocks. In any case, since vertical dikes have no true floors and, as exposed, have usually lost their summits by erosion, the mechanism of their magmatic differentiation must be incomparably less clear than in the case of well-exposed sheets. Because of their indefinite depth, wide dikes are affected by the relatively high temperatures of the country rocks in great depth, thus facilitating assimilation in the body as a whole. For the same reason, wide dikes tend to be charged with specially great amounts of magmatic gases rising from deep levels. These gases promote both assimilation and differentiation. The facts ascertained in the sheets show that gravitative differentiation should be expected in these dikes. According to the level at which the erosion surface cuts the dike, the arrangement of rock types will vary. Near its summit an expected arrangement will be as follows: at the walls a chilled phase of either the primary basalt or a more or less acidified representative of it; in the middle of the dike, a silicious phase corresponding to that at the roof of a differentiated sheet or laccolith. This phase should tend gradually to increase in acidity toward the middle of the body and to be transitional into the more femic marginal facies. The middle phase will tend toward an aplitic composition since the emanating magmatic gases must be specially concentrated in the middle of the dike.

In spite of certain complications of history, the gabbroid intrusion at the Carrock Fell of the English Lake District seems to be an illustration in point. Though Harker describes this body as a laccolith, his section shows its contacts to be steep and he regards it as probable that the mass has nearly the same attitude as that at the time of crystallization.[1] The body is 4 miles or more in length and averages

[1] A. Harker, Quart. Jour. Geol. Soc., Vol. 50, 1894, p. 329, and Vol. 51, 1895, p. 126; The Natural History of Igneous Rocks, New York, 1909, p. 133.

about 1/2 mile in width. However it is to be classified, it doubtless extends to great depth and has the essential features of a dike so far as these affect the present discussion. Harker has clearly shown the orderly succession of the dike phases, from gabbro at the walls with specific gravity greater than 2.95, through an intermediate zone of gabbroid rock with accessory quartz and a specific gravity between 2.85 and 2.95, to a middle phase (quartz gabbro) strongly charged with micropegmatite and free quartz and characterized by a specific gravity less than 2.85. Segregations of iron ore near the margins represent local differentiates in the contact phase of the gabbro.

Harker has discussed the mechanism of the differentiation which he regarded as the result of diffusion, but he makes no reference to the control of gravity. The present writer is inclined to question whether the essential features of this Carrock Fell body are not best explained by the combination of assimilation and gravitative differentiation in an original gabbro (basaltic) magma.

That intrusive body is described as only slightly older than the neighboring intrusions of granophyre (micropegmatitic granite). The consanguinity between the granophyre and the middle phase of the gabbroid intrusive is obvious and Harker suggests the possibility that all the rocks have been "derived from different portions of one deep-seated reservoir."[1] The facts certainly suggest that the granophyre is a gravitative differentiate formed in the deeper, less rapidly chilled, and hence more differentiated part of the same dike fissure occupied by the gabbro, or else in a neighboring wide dike. The mineralogy and chemistry of all these rocks so perfectly match those of many of the gabbro-granite sheets above described that the writer has been led to postulate an origin for the Carrock Fell rocks in terms of the syntectic-differentiation theory.

Similar associations of gabbroid or diabasic intrusives with independently injected micropegmatitic granites are recorded in Skye and other parts of the British Islands, as in Ontario, Minnesota, South Africa, etc., and their development is in none of these cases directly seen to be due to the activity of superheated sheet intrusions. One may suspect, however, that in some cases the syntectic process affected wide dikes, that is, injected bodies virtually like miniature batholiths. Satellitic eruption from the dike chambers has generally complicated the structural geology and petrology of these respective areas.

Origin of Normal Batholithic Granites

The secondary granites found in the differentiated sheets and laccoliths are usually somewhat abnormal in chemical composition;

[1] A Harker, Quart. Jour. Geol. Soc., Vol. 50, 1894, p. 330.

their fine grain and micropegmatitic habit is doubtless related to the conditions of comparatively rapid cooling in the presence of resurgent water. The granite of a typical batholith has wall rocks chiefly composed, not of water-laden sediments, but of pre-Cambrian gneiss and other constituents of the earth's acid shell. The batholith must cool with extreme slowness and a granular habit is therefore characteristic of its visible rock. Nevertheless, the eclectic theory, as outlined in Chapters IX to XII and XIV, holds that the normal granite of a batholith is a true homologue of the secondary granite in any one of the intrusive sheets above described. In those chapters will be found an abstract of the argument favoring the truth of this homology, and additional facts bearing on it are noted in the writer's previous writings. A new statement is not necessary in this place.

It should be noted that the eclectic theory specially relates to the late pre-Cambrian and still younger granites. The older batholiths of the Laurentian type may have been formed by the same mechanism as that illustrated in the younger batholiths; the field evidence that stoping, on a large scale, has occurred in the former is clear. Yet the universality and immense scale of the early pre-Cambrian intrusion and its apparent independence of geosynclinal zones suggest that the magmas of the oldest granites may not be differentiates of syntectics in abyssal wedges of the basaltic substratum, but simply parts of the earth's acid shell which was locally fused. Possibly the heat necessary for remelting was of radioactive origin.

This uncertainty as to the genesis of the oldest batholiths illustrates the fact that the granite problem still lacks a complete solution. An approach to it is made when it is recognized that the structural, chemical, and time relations of the rocks in a post-Cambrian batholithic area apparently all accord with the postulates and inferences of the eclectic theory as outlined in the foregoing chapters.

Granitic Magmas Differentiated from Magmas Belonging to Other Clans

Vogt states that the magmas of such rocks as monzonite, pulaskite, and most diorites are anchi-eutectics, implying that they are incapable of undergoing notable differentiation.[1] But the field evidence clearly suggests that these and some other magmas tend to split, with a granitic type as the acid pole. The eclectic theory carries the deduction that dioritic and syenitic magmas are either syntectics or differentiates of syntectics. It regards granite as the final acid pole of the earth's primitive differentiation, whereby the acid shell and the

[1] J. H. L. Vogt, Norsk Geol. Tidsskrift, Bind 1, No. 2, 1905, p. 30.

basaltic substratum became separated. It considers the final acid pole of splitting in large post-Keewatin batholiths as granite, which has preserved its ancient "antagonism" to basaltic magma. In the smaller abyssal wedges or in chambers satellitic to great batholiths, where relatively quick cooling shortens the period of liquidity, the differentiation of syntectics is often arrested midway and rocks of intermediate composition result. Under favorable local conditions a part of such an intermediate magma is allowed to split further and the final, granitic pole may be represented in phases of the parent chamber or in apophysal injections from it.

This theoretical conclusion seems to be amply supported by the facts of nature. Very commonly, diorite, quartz diorite, granodiorite, or syenite passes insensibly into granite in such a way as to suggest that the granitic magma was a late differentiate from the other magma. That the separation may be controlled by gravity is shown by the superior position of the granitic rocks in the great British Columbia, Minnesota, and Ontario sheets and laccoliths just described. Beneath the granites are phases of dioritic and granodioritic composition. An analogy is found in the Cnoc-na-Sroine laccolith at Loch Borolan, Scotland, where quartz syenites (sp. gr. 2.625-2.635) with 12 per cent. of free quartz, overlie melanite syenites (sp. gr. 2.65–2.78).[1]

Influence of Resurgent Gases.—The local assimilation of special sediments, notably those carrying large quantities of volatile matter, may produce conditions for extreme differentiation in a part of a plutonic chamber which in general is represented by crystallized rock of intermediate composition. Thus, the extensive Bayonne batholith of southern British Columbia is made up chiefly of granodiorite, while several of its small satellitic stocks are made up of the more salic biotite granite[2] (Fig. 164). This contrast may be in part explained by the fact that the existing outcrops of the granite are located near the roof level in each stock, while the batholith has been eroded to greater depth; but the stocks in question cut sediments of exceptional thickness and the differentiation of true granite may be due to the influence of water and other materials absorbed locally from the walls. On this view, the stock masses are interpreted as nearly (hypidiomorphic-granular) equivalents of aplite, which is generally agreed to have been segregated with the special aid of magmatic gases. It needs no emphasis that many aplites and pegmatites of granitic composition have been derived from bodies of dioritic, granodioritic, and syenitic composition.

Clements describes an instructive parallel from a 4-foot dike in

[1] S. J. Shand, Trans. Edinburgh Geol. Soc., Vol. 9, 1910, p. 376.

[2] R. A. Daly, Memoir No. 38, Geol. Surv. Canada, 1912, p. 301.

the Crystal Falls district of Michigan. At both contacts the dike is a true diorite, which merges, toward the middle, into a biotite granite. The small size and consequent short magmatic life of the dike excludes any possibility that the femic phase was here caused by diffusion of certain constituents to the cooling walls. The magma seems to have been splitting *during* the act of injection so that the salic pole was thrust centrally into the opening fissure already bearing chilled, undifferentiated diorite. The rapidity of the chemical change is explicable on the supposition that magmatic gases aided in the (upward) transfer of the granitic magma.[1]

Eruptive Sequence.—In composite batholiths and stocks the order of intrusion, for the *batholithic* elements, is very generally from femic to salic. (See Chapter IV.) The crystallization of one of these great

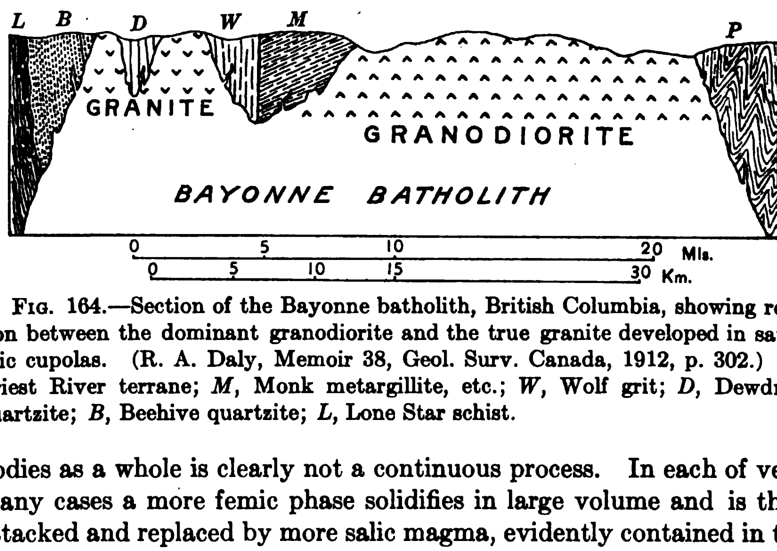

FIG. 164.—Section of the Bayonne batholith, British Columbia, showing relation between the dominant granodiorite and the true granite developed in satellitic cupolas. (R. A. Daly, Memoir 38, Geol. Surv. Canada, 1912, p. 302.) *P*, Priest River terrane; *M*, Monk metargillite, etc.; *W*, Wolf grit; *D*, Dewdney quartzite; *B*, Beehive quartzite; *L*, Lone Star schist.

bodies as a whole is clearly not a continuous process. In each of very many cases a more femic phase solidifies in large volume and is then attacked and replaced by more salic magma, evidently contained in the same abyssal chamber as that in which the solid phase had formed. Because of the quite limited depth of erosion, outcrops showing either phase must be relatively near the batholithic roof. It seems likely, therefore, that the solidified femic phase was originally a roof phase and that beneath it the more salic magma became differentiated by gravity. The fact of extensive replacement of the femic phase is fully shown in many fields and its mechanism is probably that of marginal corrosion coupled with magmatic stoping. In other words the solid femic shell at the roof is not in equilibrium with the still fluid portion of the abyssal wedge. As differentiation continues in depth, the more salic pole above, doubtless aided by juvenile and resurgent

[1] J. M. Clements, Jour. Geology, Vol. 6, 1898, p. 377.

gases concentrated within it, has power to remelt part of the solid but still hot roof-phase. The classic experiment of Morozewicz gives proof that gravitative differentiation follow such remelting. He melted two pounds of granite (with 68.9 per cent. of silica) and left the superheated melt in a hot part of an active glass furnace for five days. It was then cooled to a glass. The lower part of the melt was found to have 59.2 per cent. of silica; the upper part, 73.65 per cent.[1]

Continued assimilation of the country rocks in depth may complicate the process but there can be little doubt that a normal batholithic sequence is due chiefly to differentiation within one abyssal chamber. No other supposition can explain the detailed consanguinity in the successive rock types. Several large-scale illustrations of such relationship have been studied by the writer; a few of these may be mentioned.

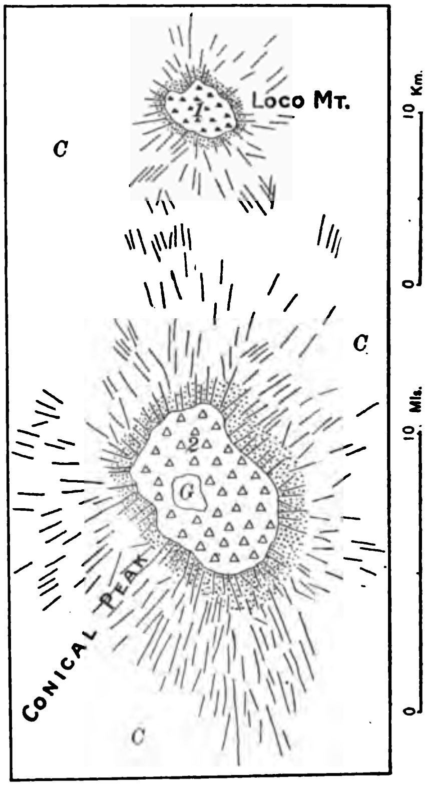

FIG. 165.—Map of intrusive stocks in the Crazy Mts., Montana. (After Little Belt Mts. Folio, No. 56, U. S. G. S., 1899.) *C*, Cretaceous, Livingston formation; *1*, Eocene diorite; *2*, Eocene quartz diorite; *G*, Eocene granite. Dikes shown by lines; contact aureoles stippled.

Differentiation from Dioritic Magmas.—The dioritic shells commonly found along the contacts of granite batholiths have already been explained as chilled phases representing the magmatic state before the granite itself was differentiated. (See p. 244 and Figs. 114, 123, 124.) The femic shell is not necessarily continuous; among other irregularities it may show that due to local caustic replacement by the granitic differentiate.

Sometimes rocks of the granitic clan are known to have been intruded in the same general eruptive period as neighboring, more femic rocks, but no evidence may be at hand that the two types are in any definite succession The visible rocks of a given region may, in fact, be quite contemporaneous, and yet there is a possibility that the acid rock is a

[1] J. Morozewicz, Tschermak's Min. and Petrog. Mitt., Vol. 18, 1898, p. 232.

differentiate of the more basic magma. An example appears in the late Cretaceous or early Tertiary intrusions found in the Clifton quadrangle of Arizona.[1] Some of these are composed of diorite porphyrite, which here characteristically forms sills and laccoliths. Others are composed of granite porphyry and quartz-monzonite porphyry, developed in stocks or in apophyses of stocks. Compared to sill or laccolith, the bottomless stock has a greater supply of heat as well as of magmatic gases risen from the depths. Both conditions

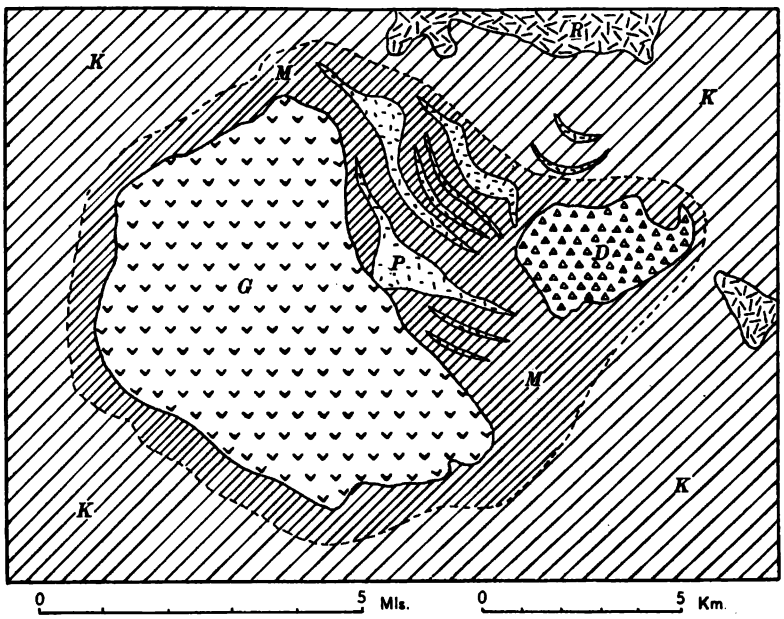

FIG. 166.—Map of intrusive stocks in the Castle Mts., Montana. (Same ref. as for Fig. 165.) *K*, Mesozoic sediments; *M*, metamorphic aureole; *D*, Neocene (Robinson) diorite; *G*, Neocene (Castle) granite; *P*, Neocene rhyolite porphyry; *R*, Neocene rhyolite.

tend to promote differentiation and it is conceivable that the acid porphyries are thus derived from the original dioritic magma.

In many other regions granite stocks and batholiths are surrounded by satellitic dikes, sheets, laccoliths, or irregular injections of diorite in such relation that the smaller bodies are only to be interpreted as apophyses from the larger bodies. The latter, with longer magmatic life, have been differentiated under the combined control of gravity and gaseous transfer, with granite as the salic pole near the roofs of the great chambers.

Weed has described striking cases in Montana. The Loco

[1] W. Lindgren, Clifton Folio, U. S. Geol. Survey, 1905.

diorite largely composes the small Loco Mountain stock and the much larger Conical Peak stock of the Crazy Mountains (Fig. 165). In the smaller stock, covering only 4 square miles, the prevailing rock is an augite-biotite diorite with no hornblende and very little quartz. The Conical Peak stock, covering 20 square miles, consists largely of a quartz diorite, containing hornblende, biotite, augite, labradorite,

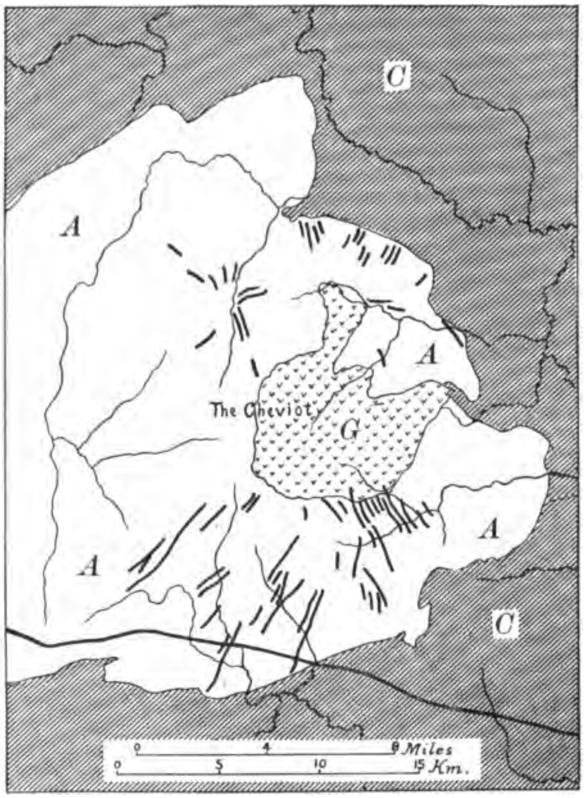

FIG. 167.—Map of the Cheviot district, England-Scotland. (After H. Kynaston, Trans. Edin. Geol. Soc., Vol. 7, 1899, p. 390.) *C*, Carboniferous; *A*, andesites; *G*, granite. Dikes shown by lines. The granite is interpreted as a late differentiate of the andesitic magma (Kynaston.)

orthoclase, and quartz. The contrast in composition is of the kind expected if, as theory directs, the larger mass, with longer magmatic life, had been more differentiated In each instance the erosion surface is not far below the roof level and the more salic differentiate is there to be expected. The splitting went still further in the larger mass, in which the quartz diorite is centrally penetrated by the slightly younger Crazy Mountain hornblende granite. Weed states that this granite is "apparently the aplitic phase of the diorite."[1]

In the same quadrangle, the Neocene monzonitic diorite of the Castle Mountains, covering about 3 square miles, lies close beside the nearly, or quite, contemporaneous Castle granite covering 23 square miles. In spatial relation at least the small diorite mass is satellitic to the much larger body of granite.[2] (Fig 166. See also Figs. 50, 114, and pages 195 and 384.)

The syngenesis of granite and effusive andesite in the Cheviot Hills of the Scottish border seems clear from their geological and petrographic relations. The granite forms a large stock cutting the andesite which evidently represents an earlier phase of the magma, before the granite was differentiated. (Fig. 167.)

Differentiation from Granodioritic Magmas.—In the Okanagan composite batholith of the Cascade Mountains, the Similkameen granodiorite (with granitic, monzonitic and dioritic phases) is cut and partly replaced by the Cathedral biotite granite. The heart of the main Cathedral body is itself cut by a less femic but closely allied granite in the form of a huge dike. Microscopic and chemical study corroborates the already compelling field evidence that these bodies are all phases of *one* batholithic mass. The granites are, therefore, to be regarded as differentiates of a magma which was granodioritic at an earlier stage.[3] Parallel cases have been recorded at intervals in the belt of composite batholiths extending from Alaska to Mexico. The intimate field association of typical granodiorite, quartz diorite, and granite in the Skagit division of the Cascade mountains has been described by the writer.[4]

The derivation of true granite from typical granodiorite is many times illustrated in the batholiths of the Western United States, especially in those of the Californian Sierra Nevada.[5]

An actual example of such differentiation in place seems to be represented at the contact of the great Trail batholith, near Rossland in southern British Columbia. There the intrusive rock is a granite porphyry, strongly charged with basic segregations reaching a foot or more in diameter. The segregations have the composition of vogesite

[1] W. H. Weed, Little Belt Mountains Folio, U. S. Geol. Survey, 1899, p. 4.

[2] Several good examples of peripheral diorite forming the chilled contact phases of granite and granodiorite batholiths are described by the writer in Memoir No. 38, Geol. Surv. Canada, 1912, pages 785, etc.

[3] R. A. Daly, Memoir No. 38, Geol. Surv. Canada, 1912, pp. 455–464 and 470–478.

[4] R. A. Daly, ibid., pp. 534–540.

[5] See, for example, the Colfax, Bidwell Bar, Truckee, Jackson, Nevada City, and Pyramid Peak Folios of the U. S. Geol. Survey.

and appear to be the femic masses "frozen in" by the salic magma simultaneously developed in the local splitting of granodioritic magma.[1]

Differentiation from Syenitic Magmas.—The syngenetic character of many true granites and syenites is obvious to the informed petrologist. The sequence of their intrusion is quite analogous to that exhibited in granite-granodiorite fields. The composite stock at Mount Ascutney, Vermont, is a specially clear case, studied rather minutely[2] (Fig. 64, p. 113).

The march of differentiation in the Kiruna district of Sweden, through a syenitic phase to a "quartz porphyry" (granite porphyry) phase of still later eruption, is particularly clear, as shown in the writings of Geijer and Lundbohm[3] (See page 397 and Fig. 204).

Other instances of the intrusion of granitic magma after, but closely associated with, syenitic magmas of the *same* petrogenic cycle may be summarized in the form of Table XVII:

TABLE XVII

Region	Earlier intrusion	Later eruption	Authority
Monzoni.........	Monzonite....	Granite...........	O. von Huber, Jahrb. K. K. Geol. Reichsanst., Vol. 50, 1901, p. 395.
Predazzo.........	Monzonite....	Granite...........	W. C. Brögger, Videnskabs. Skrifter, Christiana, I. Math.-naturv. Kl., No. 7, 1895, p. 163.
Aar massif........	Syenite.......	Hornblende granite and biotite granite.	J. Königsberger, Erläut. zur Geol. u. Miner., Karte des östl. Aare-massive, 1910.
Christiania Region	Alkaline syenites.	Granite...........	W. C. Brögger.
Ekersund-Soggendal district, Norway.	Monzonite and banatite.	Granite...........	C. F. Kolderup, Bergens Museums Aarbog, 1896, No. 5, p. 183.
Bergen district, Norway.	Mangerite, monzonite, soda-syenite.	Granite...........	C. F. Kolderup, Ibid., 1903, No. 12, p. 118.
Thousand Islands, N. Y.	Alkaline syenite.	Alkaline granite...	H. P. Cushing and others, Bull. N. Y. State Museum, No. 145, 1910, pp.39–41.
Adirondacks, N. Y.	Syenite.......	Granite (Morris type).	H. P. Cushing, Ibid., No. 95, 1905, p. 326.
Port Coldwell.....	Syenites......	Granite...........	H. L. Kerr, 19th Ann. Rept. Bureau of Mines Ontario, Vol. 19, 1910.
Belknap Mts.,... New Hampshire	Syenite.......	Aplite............	L. V. Pirsson, Amer. Jour. Science, Vol. 22, 1906, p. 507.
Tripyramid Mt.,.. New Hampshire	Monzonite and syenite	Aplite............	L. V. Pirsson, and W. N. Rice, ibid., Vol. 31, 1911, p. 288.

Here also, continued assimilation of acid country rocks in depth must affect the composition of the main body of magma, so that local

[1] R. A. Daly, Memoir No. 38, Geol. Surv. Canada, 1912, p. 348.

[2] R. A. Daly, Bull. 209, U. S. Geol. Survey, 1903, pp. 48–85.

[3] P. Geijer, Igneous Rocks and Iron Ores of Kiirunavaara, etc., Stockholm, 1910; H. Lundbohm, Guides des Excursions en Suède, No. 5, 1910, 11[e] Cong. Géol. Internationale.

granitic phases in any one of the above-named masses may not be differentiates of a preliminary syenitic phase.

Granites formed by the further splitting of syenitic magma are almost always rich in alkalies.

Granitic Aplites and Pegmatites

It is unnecessary to dwell in detail on the theory of common aplite and pegmatite. The two are known to be syngenetic at thousands of localities and may often be seen forming parts of the same dike or sill. They have crystallized from gas-charged magma, which may commonly be regarded as the residual mother-liquor of batholiths. Harker has

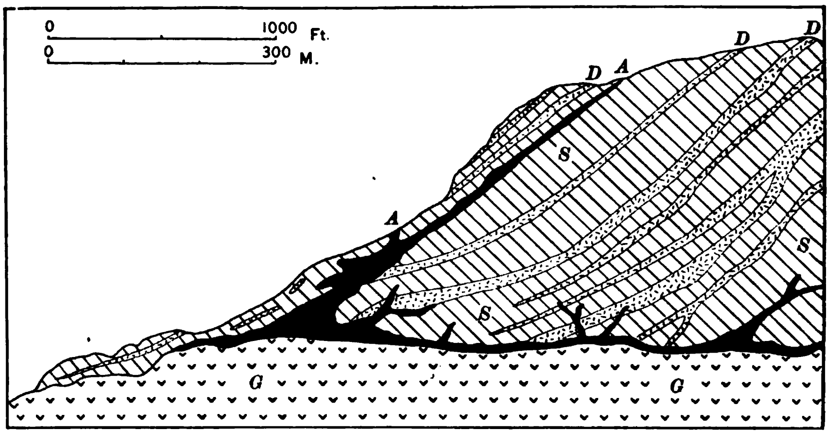

Fig. 168.—Section of Nickel Plate Mt., Hedley dist., British Columbia. (After C. Camsell, Memoir 2, Geol. Surv. Canada, 1910, p. 101.) *S*, Paleozoic limestone, argillite, and quartzite; *D*, diorite porphyry sheets; *G*, granodiorite; *A* (*solid black*), aplite. Illustrating the segregation of aplitic material at the roof of a batholith.

outlined the process by which this always subordinate phase of a batholithic magma is probably developed.[1] (See page 246.) The abundant water and other volatile materials in this salic solution are not merely "mineralizers"; they also facilitate the upward transfer of the quartz-feldspar eutectic.

Aplites approximating that eutectic in composition have been formed in large intrusive bodies which have crystallized as granite, granodiorite, quartz diorite, diorite, syenite, or even as quartz gabbro or quartz diabase; and these aplites are recorded at the roofs of sills, laccoliths, chonoliths, stocks, and batholiths, especially the last. One

[1] A. Harker, The Natural History of the Igneous Rocks, New York, 1909, pp. 293 and 323.

of the best exposed segregations of this sort yet described is that found by Camsell in the Hedley district of British Columbia[1] (Fig. 168). His section illustrates the upward and outward expulsion of the aplite from a granodiorite batholith. Weed and Barrell found another striking case in the Elkhorn district of Montana (Fig. 169).[2]

Similarly, the roof apophyses of the Monzoni granite carry over 76 per cent. of silica while the normal rock carries but 70 to 71 per cent.[3] Most of the hundreds of sills and dikes, seen to cut the fissile roof rocks of a pre-Cambrian batholith in British Columbia, are

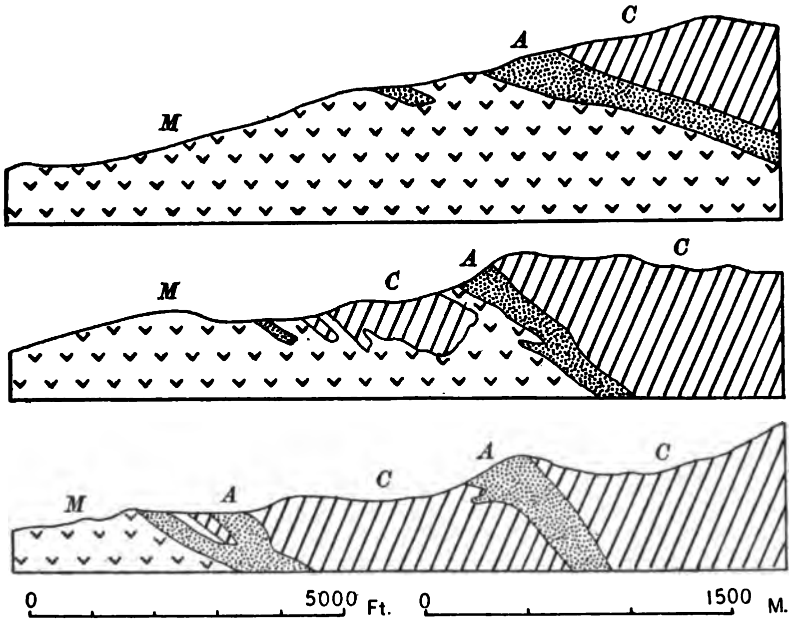

Fig. 169.—Sections in the Elkhorn Mining district, Montana. (After W. H. Weed, 22nd Ann. Rep., U. S. G. S., 1901, Part 2, p. 444.) *C*, country rocks; *M*, quartz monzonite and granite; *A*, aplite. Aplite collected at roof of batholith.

either aplitic or pegmatitic, while the main mass is common biotite granite (or orthogneiss).[4] It seems to be a fact that the pre-Cambrian batholiths were more prone to give off these satellitic magmas than the later intrusions have been.

However, one may seriously question the view that all aplites

[1] C. Camsell, Memoir No. 2, Geol. Surv. Canada, 1910, p. 101.

[2] W. H. Weed and J. Barrell, 22d Ann. Rept., Part 2, U. S. Geol. Survey, 1901, Plate 48.

[3] O. von Huber, Jahrb. k. k. Geol. Reichsanst., Vol. 50, 1901, p. 395.

[4] R. A. Daly, Guide-book No. 8, 12ᵉ Cong. Géol. Internat., Ottawa, 1913, pp. 128 and 222.

and pegmatites are derivatives from definite magma chambers. There is much to be said for the hypothesis that some of these salic rocks are due to what Lane has called "selective solution." During intense regional metamorphism, especially of the dynamic kind, deep-seated rocks, charged with much interstitial water, may reach the relatively low temperature at which minerals corresponding to the quartz-feldspar eutectic go into solution with the water and other volatile fluxes. Such small, locally generated pockets, lenses, or tongues of fluid may be driven through the solid country rock for an indefinite distance; subsequently to crystallize with the composition and habit of the true batholithic derivatives. It is thus quite possible that these particular rocks, though truly magmatic, have had no direct connection with abyssal injections.

Origin of the Rhyolitic Types

Chemically the average rhyolite, liparite, and quartz porphyry are nearly identical. Each differs from average granite in the systematic way usual for volcanics and corresponding plutonics. (See page 229 and Cols. 4–12 in Table II.) This contrast is most striking in the case of the granite clan and explanation is probably to be sought in the specially large average size of granitic magma chambers. The length of the magmatic period for a batholith must favor its gravitative differentiation. As usual, the extrusive lava is drawn from the upper magmatic phase in the plutonic chamber.

Yet there are very numerous localities where rhyolitic (liparitic) lavas have not been directly connected with batholiths but, on the other hand, have issued from much narrower abyssal wedges of the type of sheets, dikes, or central volcanic vents.

The secondary granite formed at the top of the Duluth laccolith has been extruded to the surface as true rhyolite and a similar origin in smaller bodies of injected, somewhat superheated basaltic (gabbroid) magma is highly probable for other extrusive "red rocks" in Minnesota. A thin rhyolite flow in the Purcell mountains seems to be a surface expression of the secondary magma generated in the Moyie and other sills of the range.[1]

The soda liparites, comendites, and quartz keratophyres are similarly contrasted with "alkaline" granite, but these effusive types are seldom from large batholiths, or visibly transitional into granite. It is probable that magmatic gases (both juvenile and resurgent) have played an essential part in the formation of these alkaline effusives.

Our understanding of the rhyolites evidently depends in part

[1] R. A. Daly, Memoir No. 38, Geol. Surv., Canada, 1912, pp. 211 and 219.

on the facts bearing on the origin of the granites actually seen to be differentiated in thick intrusive sheets. If these granites are accepted as derivatives of syntectics of basic magma and acid country-rocks, it is easy to credit a secondary origin for some rhyolites. Since superheat has obviously characterized the lavas of volcanic vents both active and extinct, small amounts of wall rock should, under certain circumstances, be dissolved. Two different possibilities are open.

If the dissolved country-rock is acid, gravitative splitting may form a rhyolite composed chiefly of the oxides of that foreign material, as in the differentiation of a Moyie sill.

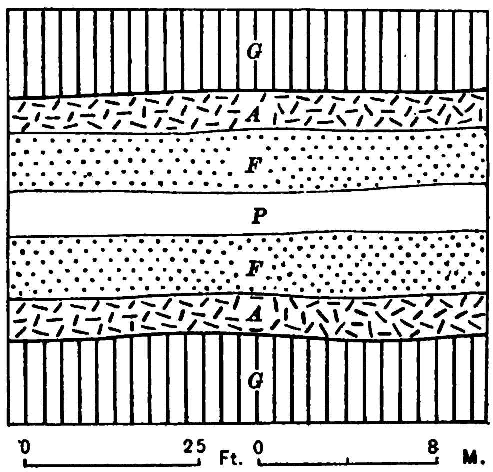

FIG. 170.—Plan of composite dike, Cir Mohr, Island of Arran. (After J. W. Judd, Quart. Jour. Geol. Soc., Vol. 49, 1893, p. 545.) *G*, granite; *A*, andesite; *F*, quartz felsite; *P*, pitchstone porphyry (like *F*, a quartz pantellerite). *A*, *F*, and *P* are successive intrusions following the same fissure.

Or the dissolved material, (resurgent water, etc.) may act chiefly as an incentive to gravitative splitting in the basic magma. In Chapter XVII will be found a digest of the argument that augite andesite is a differentiate of basalt. The ground-mass of augite andesite is rhyolitic in chemical composition. The question arises as to whether the absorption of water or other foreign material may stimulate the extreme splitting whereby rhyolite is generated from andesite, itself a differentiate of the primary basalt. The same result may be imagined in the case of a mica andesite, a dacite, or a trachyte; all the more readily since granites in so many instances have been differentiated from dioritic, granodioritic, and syenitic magmas. In all cases gravity would affect the differentiates more or less emphatically. Inasmuch as central vents are always small (see page 129), the volume of rhyolite formed in this way must be relatively small. A moderately prolonged extrusion of the upper, acid magma must cleanse it from the vent, whence may now issue flows of basic andesite or regenerated basalt, representing the femic pole of the differentiation. More prolonged extrusion finally brings the primary basalt, from still greater depth, to the surface.

Assimilation and differentiation in ever varying relative importance may thus be responsible for the extremely common alternation of rhyolitic, dacitic, andesitic, trachytic and basaltic flows at central vents. Examples are noted in the table of Appendix B. Some given in special detail are summarized under captions: "Berkeley Hills, California," "Goldfield District, Nevada," "Clifton Quadrangle, Arizona," "Rosita Hills, Colorado," "Island of Skye," and "Eolian Islands."

The syngenetic relation between rhyolites and andesites is further shown in the features of certain dikes and other small bodies which have been studied in detail.

Judd's account of the composite dikes in Arran is in point.[1] Figure 170 is a copy of one of his drawings. The dike is exteriorly composed of two sheets of augite andesite; interiorly, of two rhyolitic phases nearly identical in chemical composition. Analyses are given in the following table.

ANALYSES OF PHASES OF THE CIR MHOR DIKE, ISLAND OF ARRAN

	Augite andesite	Quartz felsite	Pitchstone porphyry
SiO_2	55.79	75.31	72.37
Al_2O_3	15.97	13.62	11.64
Fe_2O_3	12.50	2.31	1.42
FeO	.....	.....	1.08
MgO	2.22	.20	.52
CaO	7.06	.97	1.30
Na_2O	2.21	3.02	4.15
K_2O	1.86	4.07	3.98
H_2O and loss on ignition	2.43	1.48	4.86
	100.04	100.98	101.32

Other dikes of the region are similar but have dacitic and also andesitic pitchstones between the wall sheets of augite andesite! "In some cases the more acid rock (quartz-felsite and pitchstone) was the first ejected; but, quite as frequently, the basic material (augite-an-

[1] J. W. Judd, Quart. Jour. Geol. Soc., Vol. 49, 1893, p. 545.

desite) was the earliest to be intruded into the opening fissure. The relative ages of the two rocks in the dike are shown, not only by the positions which they occupy, but by the circumstance that derived minerals from the older rock are found included in the younger one."[1] Judd concludes that these magmatic types were syngenetic and became separated in depth independently of fractional crystallization. It would be difficult to find more telling illustrations of the march of differentiation among these types and it is clearly from femic to salic in the rocks actually mapped. Harker holds that the augite andesite and pitchstone "can be explained only on the supposition that the two are complementary products of differentiation of one magma."[2] The present writer believes that the andesitic, dacitic, and rhyolitic phases may be yet more readily considered to represent the successive, more *acid* poles of differentiation, the corresponding basic pole or poles being in the depths and invisible. On this view, the andesitic magma was not complementary to dacite or rhyolite but was the parent of both. The hydrous condition of the middle phase (pitchstone) of each dike suggests that water-gas actively co-operated in the formation and upward transfer of the salic magmas.

[1] J. W. Judd, op. cit., p. 561.

[2] A. Harker, The Natural History of Igneous Rocks, New York, 1909, p. 324.

CHAPTER XVII

DIORITE CLAN

Included Species

The species recognized by Rosenbusch as composing the diorite family and its dike and extrusive equivalents include the following:

Plutonic Types

Mica diorite, mica-hypersthene diorite, yentnite.
Quartz-mica diorite, tonalite.
Hornblende diorite, ornöite.
Mica-hornblende diorite.
Augite diorite.
Quartz-augite diorite, augite tonalite, quartz-hypersthene diorite, andendiorite, banatite.

Dike Types

Diorite porphyrite, augite diorite porphyrite, hornblende-mica diorite porphyrite, mica diorite porphyrite, hornblende diorite porphyrite, vintlite, paleoandesite, esterellite, microdiorite.
Tonalite porphyrite.
Garnet porphyrite.
Quartz diorite porphyrite, quartz-mica diorite porphyrite.
Paleophyrite, ortlerite, suldenite.
Diorite aplite.
Tonalite aplite.

Effusive Types

Mica andesite, mica porphyrite.
Hornblende andesite, hornblende porphyrite, asperite.
Pyroxene-biotite andesite.
Pyroxene andesite, augite andesite, augite porphyrite, carmelöite, mijakite, weiselbergite, olivine weiselbergite, hypersthene andesite, enstatite porphyrite.
Hyaloandesite.
Labradorite porphyrite, navite.
Propylites (in part).
Trachyandesite (?), ciminite (?).

Typical granite magma cannot well be considered as a direct mixture of any other known magmatic type with foreign material, either liquid or solid. Granite is often quite clearly seen to be a differentiate of more basic magmas. The greater part of the visible gabbro or basalt is interpreted as "primary" material; if its magma is a differentiate, the splitting took place before the earth's crust was completed. The species of the diorite clan are of intermediate composition and, *a priori*, they may be expected to include both differentiates and syntectics. That this judgment is probably correct will appear after a review of certain cases has been made. The genesis of some of the species presents complex problems which, because of the lack of observational data, no one has yet attacked in detail. It is impossible to list the unmodified dioritic or andesitic syntectics as contrasted with the differentiates also belonging to this clan, but very probably the great majority of its members represent differentiates of primary basalt or of its syntectics.

Andesites

Augite Andesite.—The writer has published a quantitative study of the obvious and long recognized hypothesis that augite andesite is a differentiate from basalt.[1] Some paragraphs quoted from that paper will serve to lay the case before the reader.

Petrographers are in general agreement as to the existence of many close mineralogical and chemical similarities between augite andesite and basalt. It has, in fact, been found to be impossible to draw any sharp line between the two species. Nevertheless, the olivine basalts, volumetrically the most important class of lavas on the globe, are distinctly characterized by the great abundance of the basic phenocrysts, augite and olivine, with which basic plagioclase and much magnetite are regularly associated as minerals of early generation. The list of phenocrysts in augite andesite normally includes the pyroxene and an average plagioclase which is more acid than that in the olivine basalts; olivine is absent and magnetite is less abundant than in the basalt.

As a result of numerous experiments on artificial basic melts and on natural lavas, as observed under the microscope, Doelter has proved that olivine, augite, magnetite, and plagioclase crystallize in the order which has been deduced from the microscopic study of basalt by Rosenbusch, Zirkel, and other systematic petrographers.

According to Doelter, both magnetite and phenocrystic olivine crystallize from artificial basic melts at temperatures ranging between

[1] Jour. Geology, Vol. 16, 1908, pp. 401–420.

1200° and 1030° C. The olivine largely crystallizes between 1200° and 1135° C.; the magnetite, largely between 1195° and 1100° C. The range for phenocrystic augite is 1190–960° C., with the most abundant crystallization between 1190° and 1100° C. The range for labradorite is 1125°–1075° C. He observed augite phenocrysts developed in molten basalt at the range, 1085°–920° C.; in molten limburgite at 1150° C. Magnetite formed abundantly in molten basalt at 1095° C. and in molten limburgite at various temperatures ranging from 1170° to 1065° C. For rock-melts he records only one determination for olivine, which "probably" crystallized out at 1085° C. in molten basalt.

Throughout most of the period of phenocrystic development, that is, through a fall of temperature from 1200° to about 1080° C., basaltic lava is still notably fluid. Other experiments by Doelter have shown that strong fluidity characterizes various basic lavas at the following respective temperatures:

Etna basalt	1010° C.
Remagen basalt	1060
Vesuvian lava	1080
Limburgite	1050

It is fair to conclude that at the temperature of 1050° C. the average olivine basalt is fluid, and at 1100° C. quite thinly fluid. At the latter temperature its kinetic viscosity is probably comparable to that of the Hawaiian basaltic flow which Becker has calculated to have had, at the time of its emission, a viscosity about fifty times that of water.

That olivine and augite phenocrysts are already formed in highly fluid basalt is suggested by an experiment reported (verbally, 1911) by F. A. Perret and E. S. Shepherd from Kilauea, Hawaii. By means of a cable and trolley, there installed by Professor Jaggar of the Massachusetts Institute of Technology, these observers ladled out of a characteristic "Old Faithful" fountain a mass of the molten basalt. After simple chilling in the air the rock was found to be a black glass bearing phenocrysts of olivine, augite, and basic plagioclase. From the considerable size of the crystals it seems probable that they existed in the lava lake and were not initiated during the chilling process which, however, may have allowed further growth.

A quantitative study proves that the phenocrystic olivine, augite, and magnetite of a crystallizing basalt *must* sink, provided the molten liquor remains fluid. Observation shows that the lava in volcanic pipes is kept molten through long periods. The frequently great length of the crystallization interval is explained by the conditions ruling at central vents, especially two-phase convection. In the lower part of the lava column, the juvenile gases tend to decrease the viscosity and facilitate the settling of phenocrysts. However, as long as the magma column as a whole is superheated (as at Kilauea), such crystals must be remelted in depth and two-phase convection not only remixes their material with the mother liquor but causes the repeated return of all the magma to the surface. The differentiation of andesite is thus only possible when the volcanic temperature approaches the freezing temperature of the mother liquor.

In an active volcano the time allowed for the growth and sinking of phenocrysts may be long enough for a complete differentiation, or it may suffice only to remove some of the olivine and magnetite from the cooling surface layer of the column, or it may be so short as to forbid the growth of phenocrysts in the vent. Eruption will necessarily arrest or greatly retard the process. Where the outflow is rapid and continuous, the original olivine basalt appears at the earth's surface. There, of course, the rapid cooling generally prevents recognizable differentiation in the way possible, and apparently necessary, in the vent itself where the basalt stands for a considerable time.

We have, then, to expect in nature a continuously graded series of lavas from pure olivine basalt, through olivine-free basalt, to those phases of the mother liquor which must approximate a basic augite andesite and then an acid augite andesite. The last rock would thus represent the one phase, the more voluminous phase, of this kind of differentiation. In view of the notably uniform composition of olivine basalts throughout the world, we must further expect that, in all cases where the fractional crystallization has run a complete course, the more acid phase should be relatively uniform in chemical composition. Its phenocrysts form when the magma's viscosity is relatively high and sinking is very slow.

The other products of the differentiation must also show a very great variation in composition. According to the special thermal conditions and shape of each lava column, the phenocrysts must sink to different depths and be segregated or dissolved in highly different proportions in different levels of the lava column. From the original olivine basalt many types of ultra-basic basaltic magma and of peridotitic magma might be developed in the same conduit. During energetic eruption or intrusion into the walls of the conduit these might become mixed with each other and the resulting rocks present just such great variation as is actually observed in the peridotite family. Many peridotites, the picrites, limburgites (magma basalts), and abnormal olivinitic basalts are, in this view, the rocks derived from the fractional crystallization of olivine basalt, while augite andesite or allied types represent the other pole of the differentiation.

The preliminary paper contains a discussion of this hypothesis. It appears to be substantiated by the following facts. (a) The chemical resemblance is close between typical or average augite andesite and the glassy base of an ordinary quenched olivine basalt. (b) Augite andesite and some rocks of the peridotite-picrite group are chemically reciprocal, their composition and volumes being exactly those expected if they are gravitatively derived from basalt. (c) Various authors have observed the settling of the femic phenocrysts of basalt in flow and sheet form. (See Chapter XII.) (d) Vélain describes an actual instance of such differentiation shown when augite

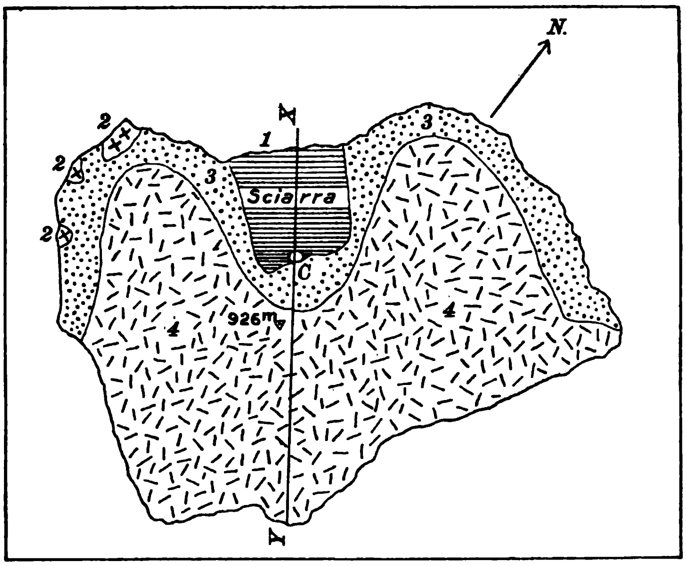

FIG. 171.—Map of Stromboli Island. (After A. Bergeat, Abhand. k. bayer. Akad. Wiss., Math.-phys. Kl., Vol. 20, 1899, Taf. 9.) *1*, youngest basalt; *2*, leucite basanite (where demonstrated); *3*, older basalt; *4*, andesitic lavas and tuffs of the original volcanic cone. *C*, crater. Scale, 1:68,000.

andesite flowed from the summit of the Réunion volcano, while ultrafemic basalts simultaneously issued from a fissure well down on its flank.

These various arguments hold good if the differentiation is purely magmatic, that is, if its units are not phenocrysts but their fluid equivalents. As indicated in the original paper, no one has yet proved that the splitting takes place by this type of liquation or by true fractional crystallization. For the purpose of making the matter clear and also subject in some degree to mathematical calculation, the writer chose to emphasize the sinking of solid crystals which, in any case, seems inevitable. The exact mode of the differentiation is not critical in the present connection. It can be safely left as an open question.

Numerous, appropriate associations of basalt and andesite on the large scale have been described by the writer in The Geology of the North

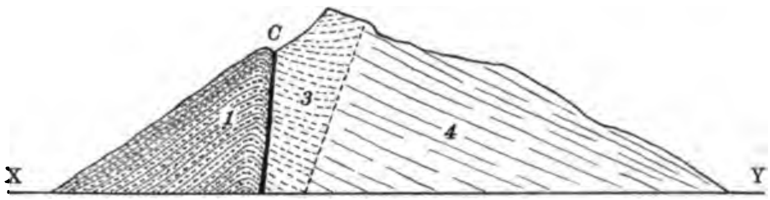

FIG. 172.—Section on line *XY* of Fig. 171. (Same ref., p. 27.) *1*, youngest basalts; *3*, tuffs of older basaltic phase; *4*, andesites and tuffs of original cone. *C*, crater. Scale, 1 : 37,000.

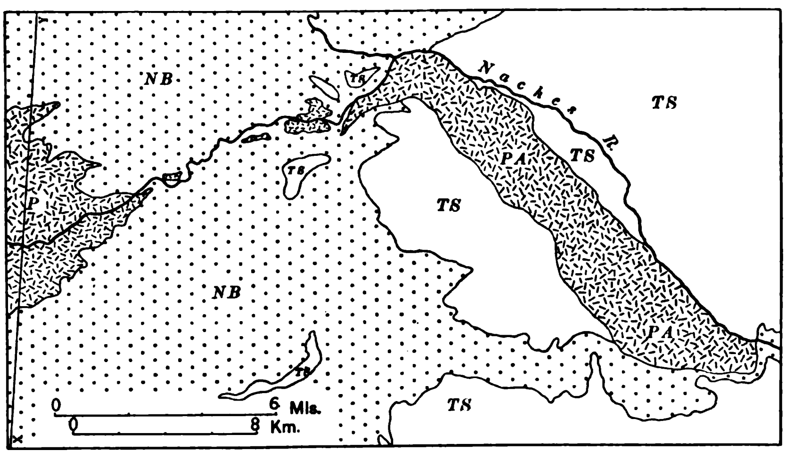

FIG. 173.—Map of part of the Ellensburg quadrangle, Washington. (After Ellensburg Folio, No. 86, U. S. G. S., 1903.) *TS*, Neocene and Pleistocene sands and silts; *NB*, Neocene basalt; *PA*, Pleistocene andesite. Illustrating the close field connection between basalt and andesite.

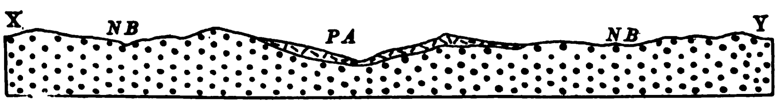

FIG. 174.—Section along the line *XY* in Fig. 173. Scale, about 1 : 250,000.

American Cordillera at the Forty-ninth Parallel.[1] Other examples of intimate field association between basalt and pyroxene andesite are recalled by Figs. 171, 172, 173, 174, and 175. (See Frontispiece.)

[1] Memoir No. 38, Geol. Surv. Canada, 1912, page 782, and other pages to be found in the general table of contents of that work.

In addition to the matter abstracted from the preliminary paper, an additional point should be noted. By the proposed explanation, augite andesite is a low-temperature submagma generated, usually if not always, under conditions like those at volcanoes of the central type. Hence careful note should be taken of the fact that, while andesite forms plentiful, generally viscous flows and yet more abundant pyroclastic phases, it never composes great fields of plateau lava like that so often developed in the basaltic fissure eruptions. Andesite is specially viscous not merely because of its chemical constitution. In all known eruptions it seems to have lacked superheat and the proper explanation of that contrast is of manifest importance.

Hypersthene Andesite.—In total volume and in geographical extension the hypersthene andesites seem to have a much greater development than the augite andesites. As shown in Cols. 47 and 48 of Table II, the two magmatic types are almost identical and the foregoing argument may be applied also to these more voluminous andesites. Rosenbusch emphasizes the perfect transition between the two types when studied petrographically and it is often illustrated in their close association in the field. Like the augite andesites, the hypersthene andesites are sometimes transitional, mineralogically, chemically, and geologically, into basalt with and without phenocrystic olivine. When we further reflect that the eruption of hypersthene andesites has been almost entirely restricted to vents of the central type, the probability that they are generally due to the gravitative differentiation of basalt becomes nearly as clear as in the case of the slightly more basic augite andesite. The mineralogical difference between the types is explicable on the assumption that the differentiation has usually proceeded a little farther in the case of hypersthene andesite. Hypersthene rather than augite would be expected in the more silicious differentiate.

Mica Andesites and Hornblende Andesites.—Many workers in andesitic regions have illustrated the very common transitions subsisting between the pyroxene andesites on the one hand and all the other types of andesites on the other. Iddings has forcibly presented the case for the lavas at Sepulchre Mountain in the Yellowstone National Park, a region which he has done much to make famous in petrography.[1] Some hornblende andesites, like some mica-bearing andesites, are chemically almost identical with a typical augite andesite. The average hornblende andesite, like the average mica andesite, is slightly more salic and less ferromagnesian than the average pyroxene andesite. These differences, though systematic, are small and their genesis is obviously a problem of extreme delicacy. The contrasts may be due in some cases to an advance in the differentiation of normal

[1] J. P. Iddings, 12th Ann. Rep., U. S. Geol. Survey, 1892, p. 647.

basalt beyond the stage registered in hypersthene andesite. The special addition of juvenile or resurgent water or other gases to the volcanic lava column may be the incentive not only to the separation of a more salic submagma, but also to the crystallization of hornblende and mica phenocrysts. The composition of the more silicious hornblende and mica andesites and their field association with acid diorite, dacite, rhyolite, or other rocks, suggest that the former extrusives are differentiates of magmas more silicious than basalt. The evidence

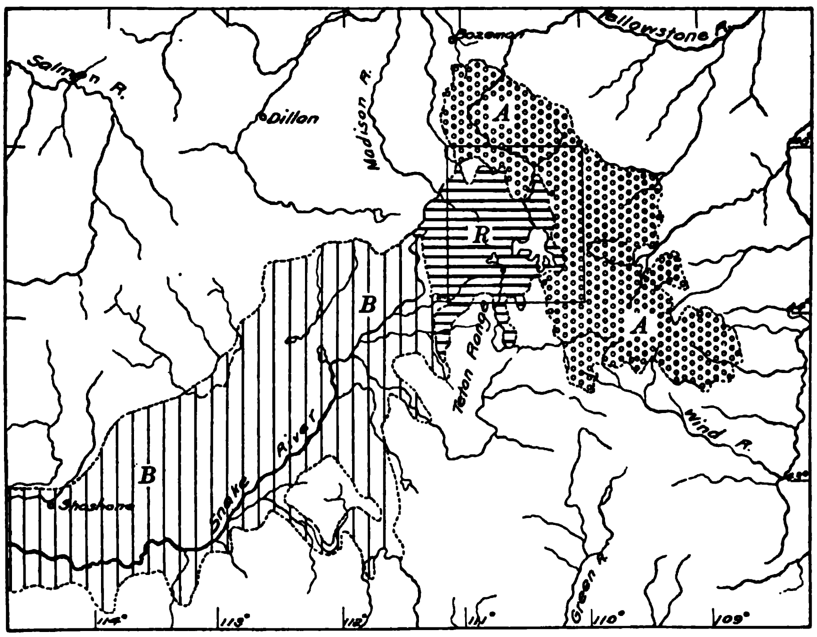

FIG. 175.—Sketch map of region embracing the Yellowstone Park, shown by rectangle. (After J. P. Iddings, Quart. Jour. Geol. Soc., Vol. 52, 1896.) *A*, andesitic pyroclastics and flows of Eocene and Miocene age (central eruptions); *R*, Pliocene rhyolite of the Park; *B*, Snake River basalt, fissure eruptions. Scale, 1:5,000,000. Illustrating rock associations expected on the eclectic theory.

as to the origin of those antecedent magmas can seldom, if ever, be won from even the most intensive study of the volcanic piles themselves. Their secret is to be found in the plutonic rocks syngenetic with the andesites. As shown by Iddings in the memoir just cited, the actual plutonic chamber can occasionally be located with reasonable certainty. The genetic problem of the more acid andesites is identical with that of some diorites. It will be noted in connection with the diorites, which, in the writer's opinion, are largely either syntectics of basalt and acid country rocks or differentiates of those magmatic mixtures.

Diorites

Some augite diorites may represent the holocrystalline phase of a pyroxene-andesite magma frozen in the generating volcanic vent or injected into the country rocks surrounding that vent. On the other hand, the field relation of many other dioritic bodies do not bear out the idea that the latter represent direct differentiates of basalt. The eclectic theory demands that the solution of the pre-Cambrian granite or orthogneiss in primary basalt shall afford the most important of all syntectics. This particular syntectic should be of dioritic composition. During solution at the main contact or at the contacts of xenoliths, the vapor pressure is nearly the same in basalt and granite (orthogneiss). The syntectic film should have about the mean composition of liquid and solid. The average composition of the pre-Cambrian terrane, down to a depth of several miles, is approximately given in the average calculated for granites of all periods or that calculated for the granites of Sweden. The former average is entered in Col. 1 of Table VIII, page 169. Column 2 shows the average composition assumed for the primary basalt. The mean of those averages appears in Col. 3, while Col. 4 shows the average diorite quite nearly. Loewinson-Lessing objects to the last average as not typical because some quartz diorites were included in making the calculation.[1] The writer included these analyses, partly because some of the "diorite" analyses used in the calculation were abnormally basic and femic and lie on or over the border-line with the gabbros. Secondly, for purposes of geological reasoning, it seemed fair to include the quartz diorites, since these diorites are so often indissolubly connected in the field. It really makes little effect on the calculated mean if the quartz diorites are excluded; this will be seen by comparing Cols. 44 and 45 of Table II.

The very close correspondence of Cols. 3 and 4 in Table VIII shows that the mutual solution of equal masses of primary basalt and pre-Cambrian granite or orthogneiss must produce an essentially dioritic magma. Loewinson-Lessing has claimed that the mean of granite and basalt is a syenite, but this cannot be true on account of the much higher content of alkalies and much lower content of lime, magnesia, and iron oxides in average syenite. (See Col. 17 of Table II.)

Since the notable assimilation of orthogneiss and allied rocks is possible only in large masses of primary basalt, it is clear that diorite of syntectic origin should be chiefly developed in subjacent bodies, that is, in stocks and batholiths. Such is undoubtedly the fact. Yet large batholiths of true diorite are unknown and those of quartz diorite are rare. The explanation has already been implied. In such large chambers

[1] F. Loewinson-Lessing, Geol. Mag., Vol. 8, 1911, p. 250.

gravitative differentiation, leading to the development of granitic types at the accessible levels, will follow the period of active assimilation. The syntectic itself should be expected to occur in two situations. It might form satellitic bodies, like dikes, sheets, laccoliths, and small stocks, all of which would chill too rapidly for differentiation. Secondly, syntectic diorite might be looked for in the contact phases of a granite batholith. (See pages 195, 365, and 384.)

Both deductions from the eclectic theory agree with the observed field relations of the diorites.

That many of the larger masses of quartz diorite and diorite have batholithic or stock form and mode of intrusion seems as clear as in the case of the granites. A notable example is found in the gigantic Coast Range body of Alaska, as described by F. E. Wright, C. W. Wright, and others.[1] Examples of dioritic stocks occur: at Mount Ascutney, Vermont; in the Crazy Mountains, Montana; in the Bradshaw Mountains, Arizona; in the Globe quadrangle, Arizona; in the Telluride quadrangle, Colorado; etc.

The evidences of intrusion by replacement, implying the assimilation of silicious country rocks, are as striking for some dioritic stocks and batholiths as they are for granitic intrusions. Abyssal solution seems inevitable in both cases and the argument for a secondary origin of the acid diorites has all the strength of that already detailed for the granites. The spatial relations, so often observed between the two species (diorites being either satellites or contact phases of subjacent granite masses), are briefly described in the last chapter; no informed petrographer needs a formal statement of the many known instances in order to agree that the theory is here matched by the facts of the field.

As above noted (page 356), Gavelin and Högbom believe that certain small dioritic bodies in Sweden are of direct syntectic origin, gabbroid magma having dissolved granite in place. A dioritic facies in the trap-dike feeders of the Cuddapah lava floods has been interpreted as a syntectic (page 356). A similar explanation is possible for the mica-diorite dikes found by Rogers among the dolerite sills of South Africa, which have clearly dissolved acid sediments, etc.[2] (See page 350.) Quite recently Miller has explained the diorites in the North Creek quadrangle of the Adirondack region, New York, as syntectics of gabbro and its acid country rocks (granite, gneiss, etc.).[3]

Harker has pointed out that hybrid rocks are generally abnormal products; "they cannot be correctly designated by names, such as

[1] F. E. Wright and C. W. Wright, Bull 347, U. S. Geol. Survey, 1908.

[2] A. W. Rogers, Geology of Cape Colony, London, 1905, p. 265.

[3] W. J. Miller, Jour. Geology, Vol. 21, 1913, pp. 177–179.

quartz-diorite, which belong to products of magmatic differentiation."[1] With this view the present writer is in accord, but it is none the less true that some intermediate phases of the Moyie, Sudbury, Palisades, and other intruded sheets, showing indubitable evidence of assimilation, approximate diorites in chemical composition. Of course these intermediate rocks are not direct syntectics but are phases arrested in the process of differentiation and thus true analogues to acid diorites. The typical diorites differ from them in just the sense demanded if the parent magma is a solution of (pre-Cambrian "acid shell") gneiss instead of water-charged sediments. The considerable diversity of composition in the diorite family is, however, explained by: (a) the variable nature of the syntectic, depending on the different proportions of gneiss, granite, schist, or sediment absorbed; (b) and the different degrees of differentiation exhibited in individual bodies. The larger the abyssal wedge, other things being equal, the more of the "granitic" earth-shell can it assimilate and the longer is its magmatic life and period of differentiation. Hence, for two reasons, the larger dioritic stocks and batholiths should generally be more acid than the small stocks. This expectation from the theory is fully matched by observed fact. The correspondence is one of the major difficulties facing the pure-differentiation hypothesis of igneous rocks.

Thus recognizing at least two quite different origins for the magmas of the diorite clan, a direct chemical comparison of the corresponding plutonic and extrusive phases is more difficult than it is in the gabbro clan or granite clan. It is true that average andesite is more salic and less cafemic than average diorite, and the dominant cause may again be found in special gravitative differentiation at volcanic vents. Yet the comparison between syngenetic members, plutonic and extrusive, still needs to be made. The fact that the lavas of this clan have pyroxene as their commonest femic constituent, while biotite is the commonest femic constituent in the plutonic types, has some definite meaning in the general problem of origins. It would seem that the direct differentiates from primary basalt predominate in the extrusives of this clan, while the syntectics predominate among the intrusives. This contrast is explicable by the root principle of the eclectic theory that the magmatic wedges feeding basaltic (and most andesitic) volcanoes are initially narrow and hence too little provided with heat energy to dissolve much of the earth's acid shell.

[1] A. Harker, The Natural History of Igneous Rocks, New York, 1909, p. 341.

CHAPTER XVIII

GRANODIORITE CLAN

Included Species

Rosenbusch regards the granodiorites as being merely varieties of quartz diorite and hence as part of the diorite family. Several writers, particularly some in America, have advocated the recognition of a separate granodiorite family, showing characters intermediate between those of typical granite and typical diorite. The great importance of granodiorite in the enormous batholiths of the North and South American Cordilleras justifies the latter view and it is a leading reason for the writer's recognition of a distinct granodiorite clan.

As the North American Cordillera is studied, the granodiorites are found to have the most intimate field association with the type called "quartz monzonite" by Lindgren and other members of the United States Geological Survey. It is probable that the rocks of the types called "quartz monzonites" by different authors working in the various continents are represented in at least as many different bodies, though not in as great total area, as the granodiorites proper. The published chemical analyses of "quartz monzonite" are about as numerous as those of granodiorite. But some of the so-called quartz monzonites (banatites, etc.) are clearly granodiorites and are often syngenetic with them; in other part, the quartz monzonites are either granites, according to the prevailing (Rosenbusch) definition of that term, or true monzonite bearing accessory or quite subordinate quartz. Many tonalites and some so-called quartz-mica diorites are chemically identical with granodiorite.

Table XVIII shows the close similarity of average granodiorite to the mean between average granite and average diorite, as well as to average tonalite. Columns 1 and 4 show how close quartz monzonite usually is to average granite, but the average in Col. 4 implies the inclusion of granodiorite types.

TABLE XVIII

	1	2	3	4	5	6	7
	Average granite	Average diorite	Mean of 1 and 2	Average quartz monzonite	Average granodiorite	Average tonalite	Average dacite
Number of analyses averaged	236	70	....	20	12	5	30
SiO_2	70.47	57.56	64.02	67.41	65.82	67.20	67.67
TiO_2	.39	.85	.62	.51	.55	.54	.33
Al_2O_3	14.90	16.90	15.90	15.76	15.99	14.71	16.81
Fe_2O	1.63	3.20	2.42	1.93	1.66	2.38	2.47
FeO	1.68	4.46	3.07	1.96	2.69	4.16	1.35
MnO	.13	.13	.13	.06	.05	.01	.04
MgO	.98	4.23	2.60	1.43	2.19	1.74	1.23
CaO	2.17	6.83	4.50	3.54	4.71	3.30	3.31
Na_2O	3.31	3.44	3.38	3.45	3.86	3.25	4.18
K_2O	4.10	2.15	3.12	3.76	2.32	2.24	2.53
P_2O_5	.24	.25	.24	.19	.16	.47	.08
	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Column 7 shows the average dacite, the chief effusive member of this clan.

The granodiorite clan thus includes the following species:

Plutonic Types

Granodiorites of the prevailing definition.
Some "quartz monzonites."
Tonalite.
Some quartz diorites.

Dike Types

Granodiorite porphyry.
Some "quartz monzonite" porphyries.
Tonalite porphyrite.
Some quartz diorite porphyrites.
Dacite porphyrites.

Effusive Types

Dacite, hyalodacite, felsodacite, biotite dacite, amphibole dacite, plagioliparite.

Quartz porphyrite, quartz-biotite porphyrite, quartz-hornblende porphyrite, vitrophyrite.

Origin

In seeking a clue to the origin of these rocks, we note, first, that the members of the clan have been reported only rarely from the greatest of all igneous terranes, the pre-Cambrian complex. Occasionally a tonalitic orthogneiss or a local body of granodiorite is mentioned, but, wherever the workers in the pre-Cambrian have stated their petrography in detail, the predominance of ordinary granites is generally clear. Nor is it fair to believe that this conclusion is essentially vitiated by the special failure of pre-Cambrian geologists to make refined petrographic distinctions. As a matter of fact, those geologists have long included a high proportion of the most ably trained and enthusiastic petrographers.

We have already seen that many, perhaps most, of the pre-Cambrian batholiths have been intruded outside of areas of heavy (geosynclinal) sedimentation. On the other hand, Paleozoic and later batholiths are almost entirely confined to such areas. The eclectic theory implies that, where sediments are batholithically replaced on a large scale, the chemical composition of both the batholithic syntectic and its more acid differentiate must be affected more or less strongly by the solution of the sediments or of the thick basaltic or andesitic beds so often laid down with the sediments. The suggestion is close at hand that rocks of the granodiorite clan are differentiates from syntectics containing considerable amounts of subsilicic sedimentary material; that these eruptives are, therefore, largely of Paleozoic or later date.

The writer was first drawn to that conception of the origin of the granodiorite clan by compiling the facts recorded concerning the field relations of the granodiorites, "quartz monzonites," quartz-mica diorites, and dacites in the North American Cordillera. These eruptives regularly cut argillaceous rocks of great initial thickness. Through close folding the mass of slates or other argillites has been notably thickened in the zones affected later by batholithic intrusion. Like the argillites, occasional limestone formations and bodies of basic lavas have been assimilated in abyssal wedges of first-class dimensions.

The evidences of replacement and assimilation are clear for the Cordilleran granodiorites. Obviously, one cannot declare the exact composition of the syntectics, which in depth will consist partly of the pre-Cambrian gneisses, as well as of the sediments or basic volcanics from wall and roof. Neither is the differentiation of these complex solutions to be traced in detail. In general, however, the abnormally basic syntectic should have an abnormally basic differentiate.

Granodiorite and its close associate, quartz diorite, do show chemical composition which must be rated as abnormal for batholiths as a whole and deviating from the normal (granite) in the direction theoretically demanded. In short, granodiorites seem to show sedimentary control on the largest scale.

Nevertheless, even the Cordilleran batholiths often indicate that granodiorite or quartz-mica diorite is not the final term in their differentiation. In many places they pass insensibly into, or are cut by, granites or salic "quartz monzonites." Chapter XVI contains reference to the repeated suggestions that these acid types are themselves differentiates of granodioritic magma. Evidently the splitting has not gone to the extreme more often, because the magmatic life of each batholith was limited. That life is dependent on heat supply. In these cases enormous quantities of heat must have been absorbed in digesting the rocks replaced in great volumes. The same was true of each batholith composed of normal granite, but in it the syntectic was initially more acid and the magmatic period needed not to be so prolonged to afford a granitic differentiate. Thus, for two reasons, the abundance of quartz diorites and mica diorites and the comparative rarity of true granite in California, Washington State, British Columbia, Alaska, etc., are not surprising features of the great granodiorite field of North America.

The writer has not attempted to compile a full list of the recorded occurrences of granodiorites and their allies, but a partial review of maps and memoirs shows abundant field data supporting the idea of sedimentary control. So far as the nature of the country rocks is concerned, this support is evident in the regions bearing granodiorites or quartz diorites, here named:

Coast Range batholith (and satellites) of Alaska, British Columbia.
Many other smaller masses in Alaska and Yukon.
Vancouver Island.
Interior Ranges and Interior Plateaus of British Columbia.
Many bodies in Washington, Oregon, Idaho, and Montana.
Absaroka Range, Wyoming.
Black Hills, South Dakota.
Several areas in Utah.
Many districts in Colorado, Nevada, New Mexico, and Arizona.
Sierra Nevada and satellites, California.
Coast Range of California.
Lower California.
Many districts in Mexico.
Southern Appalachians.
Massachusetts.
Chibougamau, Quebec.
Larder Lake, Ontario.

Sudbury, Ontario.
Glen Coe, Scotland.
Adamello, Tyrol.
Urtini Highlands, Siberia.
Many districts in New South Wales, Queensland, Victoria, and South Australia.

These regions include nearly all the known *volume* of granodioritic types and many of them contain the corresponding effusive, dacite. The relation of dacite eruptions to country rocks (so largely covered by the volcanics) is obviously often more obscure, but it is certain that most of the dacites described from the American Cordilleras have been erupted through relatively basic terranes. This is true, for example, for many localities in the Northern Andes, where granodiorites do not crop out.

The authors of the many memoirs relating to the Cordilleran granodiorites have very rarely raised the point as to how the granodiorites were intruded or that as to the origin of the magma. Ransome states that fusion and assimilation of the invaded schists in the Mother Lode district have taken place "at least to some extent." More recently Clapp has concluded that the granodiorites of Vancouver Island (cutting thick basic sediments and greenstones) have been emplaced by magmatic stoping and also show some evidences of assimilation in place.[1] Cairnes explains the intrusion of the Wheaton District granodiorite (Yukon Territory) in the same way.[2]

Emerson saw very clearly the evidences of batholithic replacement by tonalitic (monzonitic) magma in Old Hampshire County, Massacusetts. He considers the tonalite stocks of the region to be partially denuded domes of great granitic batholiths, "which have melted so much of the gneiss and hornblende-schist into their mass that their composition has been greatly changed, but which, penetrated more deeply, would change to ordinary granite."[3] Though this "tonalite" has the chemical composition of monzonite, the genetic principle stated by Emerson might conceivably also be applied to the Californian granodiorites which are in similar cross-cutting relations to the basic sediments and schists. Is it possible that the Cordilleran granodiorites are syntectics of these country rocks with an initially granitic magma? The writer is inclined to answer the question with an emphatic negative. If this hypothesis were correct, we should expect the Jurassic and older strata of the Sierra Nevada to be cut by satellitic dikes or other injections composed of the initial granite *before* the granodiorite magma

[1] C. H. Clapp, Memoir No. 13, Geol. Surv. Canada, 1912, p. 110.
[2] D. D. Cairnes, Memoir No. 31, Geol. Surv. Canada, 1912, p. 76.
[3] B. K. Emerson, Monograph 29, U. S. Geol. Survey, 1898, p. 310.

had, through assimilation, reached the observed levels in the earth's crust. It is hardly possible that such vast intrusions of acid magma affected the late Jurassic Sierra Nevada without an early fissuring of the country rocks. As a matter of fact, the late Mesozoic eruptions in the Sierra Nevada are in the order of increasing acidity, from basalts, gabbros, and the closely related basic andesites, through granodiorite, to granite and aplite. The satellites and the chilled contact phases of the

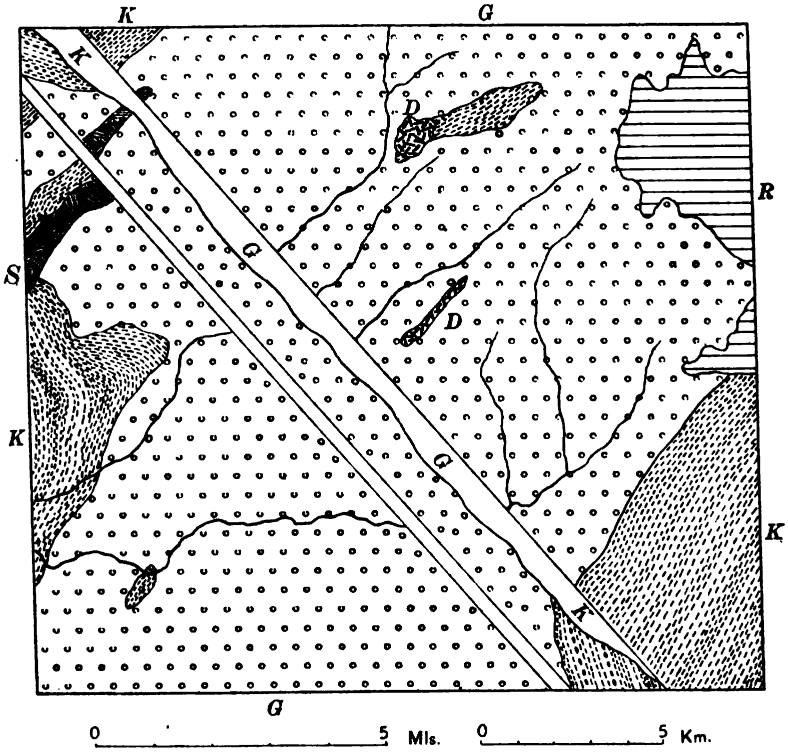

FIG. 176.—Map and section of part of the Roseburg quadrangle, Oregon. (After Roseburg Folio, No. 49, U. S. G. S., 1899.) *K*, Cretaceous, Myrtle formation (conglomerate, sandstone, and shale); *S*, serpentine; *G*, metagabbro; *D*, dacite; *R*, rhyolite.

granodiorites are usually gabbros, diorites, or porphyrites. In nearly all of the many Sierra Nevada folios of the United States Geological Survey the statement is repeated that the granodiorite locally merges into quartz diorite or diorite, less often into true gabbro. The pyroxene andesite of Mount Baker, with the associated basalts, rests on a terrane rich in granodiorite, which itself cuts older basalts of the region. These relations are typical of much of this Cordilleran intrusion. (See Frontispiece.)

Similar relations as to geological structure, order of eruption, and phasal variation are characteristic of the granodiorites of Washington State, British Columbia, and Alaska. In all these regions the field facts seem to be best explained on the assumption that in every instance the magma initiating the petrogenic cycle was of basaltic composition. That magma must have had great volume, of the order of the hypothetical abyssal wedge.

There are few recorded cases where granodiorite has been differentiated in sill or laccolith—yet rock of this composition is a principal phase of the Sudbury sheet. Its origin offers essentially the same problem as that of the likewise micropegmatitic granite in the same body. (See page 347.)

In the Port Orford quadrangle of Oregon, Diller has mapped large gabbroid intrusions which seem to have laccolithic or chonolithic relations to the thick Cretaceous sandstones and shales and pre-Cretaceous argillites and phyllites of the region. The gabbro has

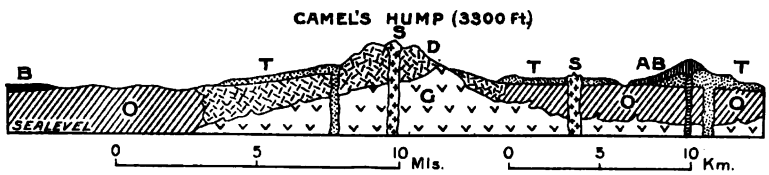

FIG. 177.—Section of Mt. Macedon, Victoria. (After E. W. Skeats and H. S. Summers, Bull. 24, Geol. Surv. Victoria, 1912.) *O*, Ordovician shale and sandstone; *G*, granodiorite; *D*, dacite; *S*, sölvsbergite; *T*, anorthoclase trachyte; *B*, normal basalt; *AB*, andesitic basalt. Illustrating field relations between granodiorite and argillites; also its intimate association with dacite and alkaline rocks.

dacitic phases. In the field Diller interpreted certain dikes in the sediments as apophyses from the gabbroid masses. These dikes are composed of dacite porphyry or of granodiorite.[1]

A similar association was found by Diller in mapping a very large mass of metagabbro in the adjacent Roseburg quadrangle (Fig. 176). It has concordant (laccolithic?) contacts with the Cretaceous beds, here largely shales with sandstone, conglomerate, and limestone interbeds. One patch of Cretaceous strata, lying within the gabbro and probably part of the roof, is cut by dacite porphyrite. The gabbro itself is said to be cut by dacite dikes.[2] One is reminded of the analogous positions of the red secondary granite in, and apophysal from, the diabasic sheets of Minnesota, Cape Colony, etc. The acid rocks are clearly differentiates and they have the relation to gabbro and sediments which is appropriate to the explanation here favored. Indeed,

[1] J. S. Diller, Port Orford Folio, U. S. Geol. Survey, 1903, pp. 3–4.

[2] J. S. Diller, Roseburg Folio, U. S. Geol. Survey, 1898.

these Oregon bodies seem to represent on a small scale the grand petrogenic events signalized in the California or British Columbia batholiths.

An instructive parallel is found at Mount Macedon, Victoria, Australia (Fig. 177). There the syngenesis of dacite and granodiorite is very clear and both are in appropriate association with thick mediosilicic sediments. The alkaline eruptives of Mount Macedon are types explained, in the next chapter, as also due to sedimentary control.

CHAPTER XIX

SYENITE CLAN

INCLUDED SPECIES.

Most petrographers are following the lead of Rosenbusch in recognizing within the syenite family a "lime-alkali'' or subalkaline series of rocks and also an alkaline series. In the present chapter we shall also include the monzonites and their extrusive equivalents in the syenite clan, without necessarily taking sides on the question whether or not monzonite is a member of the syenite *family*. The aim of this work is not to present a systematic classification of rocks but to emphasize genetic relationships. From this point of view the informed petrologist will hardly take exception to the plan of connecting intimately the monzonites and latites on the one hand with the syenites and trachytes on the other.

The following list of the clan members has been compiled from Rosenbusch's work.

Plutonic Types

A. Sbualkaline (lime-alkali) syenites.
   - Mica syenite, durbachite.
   - Hornblende syenite.
   - Pyroxene syenite, diopside syenite, uralite syenite.

B. Alkaline syenites.
   - Nordmarkite.
   - Pulaskite.
   - Hedrumite.
   - Umptekite.
   - Sodalite syenite.
   - Riebeckite syenite.
   - Arfvedsonite syenite.
   - Analcite syenite.
   - Nosean syenite.
   - Alkaline pyroxene syenite, akerite, hypersthene akerite, hornblende akerite, aegerite-augite syenite, aegerite syenite, laurvikite.

C. Monzonites.
   - Monzonite proper.

Olivine monzonite.
Kentallenite.

Dike Types

A. Subalkaline (lime-alkali) Types.
Syenite porphyry, hornblende syenite porphyry, augite (diopside) porphyry.

B. Alkaline Types.
Nordmarkite porphyry.
Pulaskite porphyry.
Umptekite porphyry.
Akerite porphyry.
Aegerite syenite porphyry.
Laurvikite porphyry.
Tönsbergite, tönsbergite porphyry.

C. Monzonitic Types.
Monzonite porphyry.
Monzonite aplite.

Effusive Types

A. Subalkaline (lime-alkali) Types.
Orthophyre, biotite orthophyre, hornblende orthophyre, pyroxene orthophyre.
Hypersthene trachyte, biotite-hypersthene trachyte, toscanite.
Some hyalotrachytes.

B. Alkaline Types.
Trachyte proper.
Phonolitic trachyte.
Sodalite trachyte.
Haüynite (nosean) trachyte.
Catophorite trachyte.
Kaimekite.
Arfvedsonite trachyte.
Aegerite trachyte.
Rhomb-porphyry, kenyite.
Keratophyre, atatschite.
Some hyalotrachytes.
Sanidinite.

C. Latitic Types.
Latite, augite latite, biotite latite, amphibole latite.
Some trachyandesites.
Ciminite.
Vulsinite.

General Statement of Origin

The eclectic theory implies that the members of the syenite clan are differentiates of secondary solutions. The theory undergoes a specially rigorous test when it is applied to the explanation of these numerous species. In making it we shall first review the principal deductions from the basal assumptions and then inquire as to the degree in which those expectations are satisfied by the facts of nature.

1. Since basaltic magma is the primary solvent, we should expect members of the gabbro clan to be often visibly associated with syenites and trachytes.

2. Granting that the normal differentiate from the syntectic of basalt and the earth's acid shell is a granite bearing much free quartz, it follows that a syenite (like a granodiorite) is a differentiate from a syntectic of contrasted composition. That syntectic must be desilicated relatively to that from which a granite is produced. The only abundant crust-rocks available for such a syntectic are basic sediments and, in a far less degree, basic igneous rocks. The theory seems, therefore, to demand that generally the members of the syenite clan shall show close field association with basic sediments or with basic igneous rocks, or with both classes of material. It is not essential that these rocks shall crop out at the same level as the erupted differentiate; on the contrary, evidence should be sought that such country rocks were once in contact with the primary basaltic wedge in *depth* where their solution was possible.

3. Since a very large abyssal wedge, with average initial temperature, is likely to dissolve much of the earth's acid shell as well as the basic material with which it may contact, its syntectic magma will, in general, yield a granite or granodiorite by differentiation. The eclectic theory, therefore, implies that the abyssal wedge from which pure syenitic magma is differentiated is usually small. The rock-bodies belonging to the syenite clan should be comparatively small in both area and volume.

In Appendix C, the reader will find a table of the principal localities where the syenite family and the family of trachytes and quartz-free porphyries are known to be represented. The species of this clan and many of the syngenetic species are listed in the second column of the table. The third column lists the sedimentary formations traversed by the respective syenite, trachyte, or porphyry. This column is incomplete, partly because of the failure of record by the observers who have described some syenitic or trachytic bodies.

Association with the Gabbro Clan.—A fairly complete review of the literature regarding the syenite clan shows that its members are very often, if not generally, in intimate association with basaltic or gabbroid types. In hundreds of areas trachyte and basalt compose volcanic piles and often form alternating flows. In scores of regions syenites and monzonites belong to the same petrogenic cycles as adjacent gabbros, diabases, basic porphyrites, norites, or similar chemical species. Not only are many known rocks intermediate between gabbro and monzonite, between gabbro and syenite, between basalt and latite, between basalt and trachyte; within a single body syenite or monzonite is often transitional into gabbro, diabase, or anorthosite.[1]

Where gabbro and syenite of the same petrogenic cycle are intruded at different times, the gabbro is generally the earlier intrusion. The sequence is thus analogous to that characterizing granite or granodiorite and gabbro, in like circumstances. The succession of plutonic types is, here again, the same as that deduced from the eclectic theory.[2] In a considerable number of instances syenitic intrusions have been immediately preceded by syngenetic essexite intrusions. As will be more specially noted in the next chapter, essexite is best interpreted as a modified gabbro. Like monzonite it passes insensibly into typical gabbro. The oldest member of the composite forming Mount Ascutney, Vermont, is thus composed of dominant basic diorite, often essexitic in habit and merging into true gabbro. This stock was cut by the nordmarkite-umptekite and pulaskite stocks of Ascutney and Little Ascutney Mountains. Adams states that essexite is represented in all eight of the Monteregian Hills of Quebec (Fig. 178). In at least six of them (perhaps all eight) the essexite is associated with syenitic magma. Adams notes also that the larger ("more easterly") masses contain proportionately more syenite and the smaller ("western") masses a greater proportion of the essexite.[3] This distribution of types is explained by the eclectic theory which implies that assimilation and differentiation will both, as a rule, progress farther in a larger body than in a smaller. The theory also implies that there should be no simple order of extrusion where basalt and trachyte or latite have emanated from volcanoes of the central type; just as there is no fixed sequence for rhyolite and basalt. The reason that these extrusions are in more complex time relations than

[1] Examples are found in the Telluride quadrangle, Colorado, mapped by the U. S. Geological Survey (p. 7 of the folio); in the anorthosite districts of Norway; in the diabasic intrusions of the Shinumo and Globe districts of Arizona, as described on pages 233, 243, 336, and 406.

[2] Compare sequences (Appendix B) at Mount Ascutney, Vermont, Tripyramid Mountain, New Hampshire; in the Adirondack Mountains, New York; North Central Wisconsin; Southern British Columbia; Predazzo, Tyrol; Christiania region, Norway; Ekersund-Soggendal district, Norway; Kiruna district, Sweden.

[3] F. D. Adams, Jour. Geology, Vol. 11, 1903, p. 251.

the corresponding intrusions has already been noted on page 288. So far as the records go, the trachytes of France, Germany, Western United States, Australia, etc., do show caprice in their times of eruption in comparison with the basalts of the same cycle.

The Kiruna district of Sweden affords a remarkably systematic sequence among rocks which have been interpreted as partly extrusive and partly intrusive. The table on page 398 states average analyses calculated for the Kiruna rocks as described by Lundbohm and Geijer. (See page 453.). Column 1 shows the computed composition of primary basaltic magma (water-free). Columns 2 to 7 show the averages

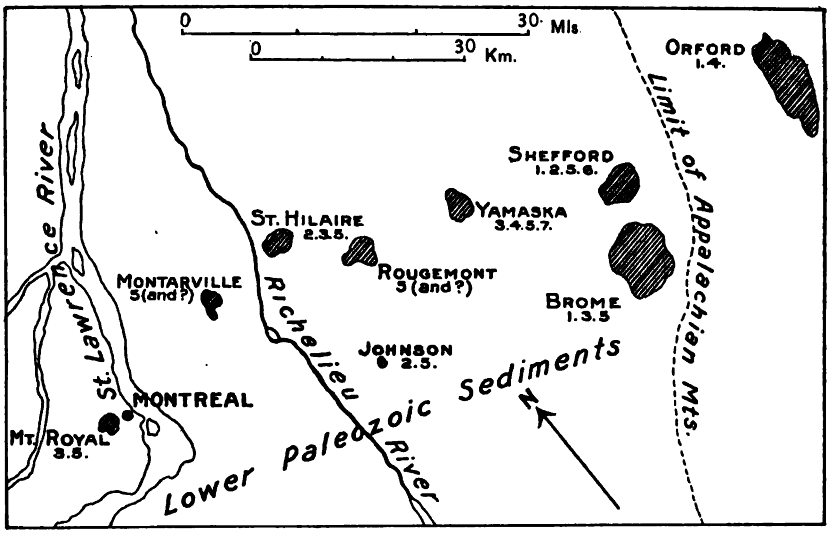

Fig. 178.—Map of the Monteregian Hills, Quebec. (After F. D. Adams, Jour. Geol., Vol. 11, 1903, p. 241.) Showing rock occurring in each intrusive body. *1*, nordmarkite; *2*, pulaskite; *3*, nephelite syenite and laurvikitic syenite; *4*, monzonite and akerite; *5*, essexite; *6*, theralite; *7*, yamaskite (jacupirangite).

of the Kiruna rocks, arranged in the order of eruption except that Cols. 4, 5, and 6 refer to the same great body.

The eclectic theory implies an *indirect* field association of the syenite clan with basalt. If post-Keewatin granites, diorites, granodiorites, nephelite syenites, as well as syenites, etc., are generally differentiates of syntectics, syenites should sometimes be clearly derivatives from the same abyssal (initially basaltic) wedge in which any one of the other plutonic types has been generated. According to the local variations in the proportions of basic sediments, basic volcanics, or granitic (gneissic shell) material assimilated by the basaltic wedge, the syntectic and therefore its polar submagmas should vary.

Syenites are often transitional into granite, diorite, granodiorite, or nephelite syenite. In each case independent bodies of these rocks show evidence of consanguinity with adjacent masses of syenite. Monzonite is not only intermediate in composition between gabbro and syenite; its intrusion is sometimes intermediate in time between those of gabbro and syenite belonging to one petrogenic cycle.

	1	2	3	4	5	6	7
See page 397	World basalt	Diabase	Soda-green-stone	Syenite	Syenite porphyry	Whole syenitic body	Quartz porphyry
No. of analyses averaged	215	1	2	2	3	5	8
SiO_2	49.65	50.46	52.90	56.44	60.60	58.94	69.41
TiO_2	1.37	.60	1.37	1.81	1.22	1.45	.38
Al_2O_3	16.16	20.08	14.20	14.67	16.21	15.59	13.92
Fe_2O_3	5.31	2.00	3.15	8.21	3.79	5.56	3.33
FeO	6.40	5.56	8.99	2.95	2.26	2.54	1.52
MnO	.29	.10	.14	.21	.22	.22	.04
MgO	6.48	6.27	3.82	2.21	2.03	2.10	.64
CaO	9.30	10.33	7.31	3.90	3.91	3.90	.89
Na_2O	3.10	3.56	5.72	6.20	6.28	6.25	5.49
K_2O	1.48	.68	.70	2.73	2.87	2.81	3.08
H_2O	....	.60	.96	.55	.54	.56	.69
P_2O_5	.46	.12	.07	.22	.19	.20	.05
S	....	.03	.04	.01	....	....	.02
CO_2	....	....	.64	....	....	....	.52
	100.00	100.39	100.01	100.11	100.12	100.12	99.98

A few concrete illustrations will suffice to point the general truth of the deductions.

In the La Plata quadrangle, Colorado, monzonite is visibly

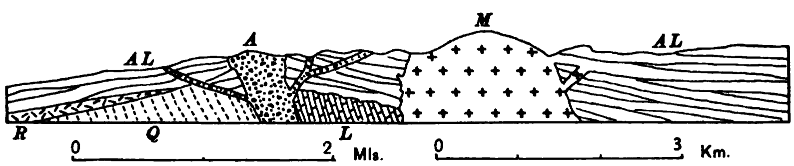

FIG. 179.—Section at Tintic, Utah. (From Tintic Special Folio, No. 65, U. S. G. S., 1900.) Showing sediments and monzonite in relations which are appropriate to the eclectic theory. Q, Cambrian quartzite; *L*, Carboniferous limestone; *R*, rhyolite; *AL*, extrusive andesite and latite; *M*, monzonite.

transitional into diorite. (See folio of the U. S. Geological Survey.) The olivine syenite of Cripple Creek merges into normal olivine gabbro as well as into pyroxene syenite and pyroxene granite.[1] The "Sunlight

[1] L. C. Graton, Prof. Paper No. 54, U. S. Geol. Survey, 1906, p. 55.

intrusives" of northwestern Wyoming are composed of quartz syenite, syenite, diorite, and gabbro, all merging into one another.[1] The Stinkingwater Peak body of the Crandall quadrangle is composed of syenite accompanied by smaller bodies of monzonites and diorites. The contemporaneous Crandall Basin intrusion is composed largely of diorites and orthoclase gabbros. In the Elkhorn district, Montana, diorite is transitional into shonkinite and quartz diorite.[2] The granodiorite batholith of southern Vancouver Island becomes monzonitic or dioritic where it contacts with thick Paleozoic limestone.[3] The monzonite of Tintic, Utah, has replaced basic sediments and is syngenetic with andesite as well as latite (Fig. 179).

Sedimentary Control.—For the purpose of estimating the kind of influence exerted on syntectics containing a considerable proportion of sedimentary material, we may use Clarke's composite analyses.[4] These are entered in Table XIX, where also the averages of eighteen analyses of phyllites and of fifteen analyses of metasedimentary mica schists are entered.[5]

As compared with the average pre-Cambrian rock (the acid earth shell), all these sedimentary types except the sandstones must exert a desilicating effect on a batholithic syntectic magma. Other things being equal, the salic differentiate from a mixture of primary basalt, gneiss, and shale, phyllite, or limestone must be lower in silica than the salic differentiate from a basalt-gneiss syntectic. An analogous effect would be wrought by the incorporation of greenstones, chloritic schists, or basic traps in a batholithic magma.

The possible variety of such mixtures is infinite. The conditions for differentiation and its ultimate product must be infinitely varied, at least within the chemical limits set by each mixture. The immense complexity of the whole process clearly forbids its systematic analysis. At present no more can be profitably undertaken than the untangling of a few rules governing the differentiation. The matter is more capable of discussion in the case of the limestone-basalt syntectic, and the next chapter describes the writer's attempt to trace the effect of the solution of carbonate rocks on subalkaline magmas. That example will be found to strengthen belief in the reality of a secondary

[1] Absaroka Folio, U. S. Geol. Survey, 1899, p. 6.

[2] W. H. Weed and J. Barrell, 22d Ann. Rept., U. S. Geol. Survey, Pt. 2, 1901, p. 446.

[3] C. H. Clapp, Summary Report, Geol. Surv., Canada, 1909, p. 89. In Memoir No. 13 of the same Survey, 1912, p. 105, Clapp suggests a syntectic origin for these contact phases.

[4] F. W. Clarke, Bull. 491, U. S. Geol. Survey, 1911, p. 28.

[5] The schist analyses averaged are to be found in Rosenbusch's "Elemente der Gesteinslehre" 3d edition, 1910, pp. 561 and 630.

origin for the species of the syenite clan, however complicated may be their chemical evolution.

TABLE XIX

No. of specimens averaged	Composite analysis of sandstones	Composite analysis of shales	Average analysis of phyllites	Average analysis of mica schists	Composite analysis of limestones
	253	78	18	15	345
SiO_2	78.66	58.38	57.1	59.7	5.19
TiO_2	.25	.65	1.0	1.3	.06
Al_2O_3	4.78	15.47	20.6	18.8	.81
Fe_2O_3	1.08	4.03	5.5	2.9	.54 (with FeO)
FeO	.30	2.46	4.6	4.0	
MnO	Tr.	Tr.	.1	.1	.05
MgO	1.17	2.45	1.9	1.9	7.90
CaO	5.52	3.12	.6	2.4	42.61
Na_2O	.45	1.31	1.6	2.9	.05
K_2O	1.32	3.25	3.7	3.3	.33
H_2O	1.64[1]	5.02	3.3[2]	2.6[2]	.77[1]
P_2O_5	.08	.17	....	.1	.04
CO_2	5.04	2.64	....	....	41.58
S	....	....	....	....	.09
SO_3	.07	.65	....	....	.05
Cl	Tr.	....	....	....	.02
C, organic	....	.81	....	....	....
	100.36	100.41	100.0	100.0	100.09

The sedimentary syntectic should illustrate the stubborn tendency of potash and soda to unite with the maximum amount of alumina and silica. In general, both oxides are present in amount sufficient for the formation of the orthoclase and albite molecules. Hence the greater volume of the differentiates from these syntectics are feldspathic and free from feldspathoids (nephelite, leucite, sodalite, etc.). The syenite clan is, in fact, volumetrically much more important than the nephelitic and leucitic clans combined.

Many species of the syenite clan illustrate a concentration of feldspathic and other alkaline material. The common segregation of such material in pegmatite and aplite dikes, its observed interstitial transfer into the roof rocks of intrusive bodies (*e.g.*, adinoles) and into miaroles, vugs, true veins, etc., are good grounds for belief that the concentration of alkalies in many syenites and trachytes is partly due to gaseous transfer. Quite recently Brauns has offered a mass of proofs that the alkalies in combination with alumina have been abundantly transferred upward in the magma chambers which fur-

[1] Organic matter included.

[2] Loss on ignition included.

nished the celebrated projectiles in the Laacher See volcanic breccias.[1] Martius notes the excessive amount of gas contained in the trachytic magma furnishing the trass and pumice of this region.[2]

The eclectic theory assumes the justice of this principle which has been so particularly discerned by the French petrologists. It is a clear advantage of the proposed theory of the syenitic species that the volatile matter required for the segregation of the alkalies is necessarily abundant in the average sedimentary syntectic. The following table illustrates the point.

Per cent.	Composite sandstone	Composite shale	Average phyllite	Average mica schist	Composite limestone
H_2O	1.64[3]	5.02	....	....	.77[3]
CO_2	5.04	2.64	....	....	41.58
SO_3	.07	.65	....	....	.05
Cl	Tr.	....	....	....	.02
Water and loss on ignition	....	....	3.3	2.6	....
Total	6.75	8.31	3.3	2.6	42.42

These relatively abundant "resurgent" gases must greatly affect the chemical equilibrium of the syntectic, which already contains the juvenile gases of the primary basalt. Whatever effect the gases may have, it accentuates the direct influence of gravity on the magmatic solution. The transfer of the alkalies should generally be upward. Several kinds of evidence tend to corroborate these theoretical views.

As noted below, trachyte and its effusive allies are slightly more salic than the corresponding plutonic species. (See Table II.)

The dominance of hornblende and mica among the femic constituents of the clan shows, in general, the presence of magmatic water in quantity at least ample enough to ensure the crystallization of these minerals. Miller has lately suggested that the alternating shells of monzonite, syenite, hornblendite, and "biotite schist" developed at the contact of a gabbro stock in Warren County, New York, are due to the action of magmatic gases. This gabbro locally cuts granite but is younger than the thick Grenville limestones and other pre-Cambrian basic formations of the region. Are the gases responsible

[1] R. Brauns, Neues Jahrb. für Miner., etc., B. B. 34, 1912, pp. 169–175; ibid., B. B. 35, 1912, pp. 211–218.

[2] S. Martius, Verhand. Naturhist. Ver. preuss. Rheinlande und Westfalens, 68 Jahrgang, 1911, pp. 381–463.

[3] Organic matter included.

for these remarkable contact effects, of resurgent origin?[1] Geijer concludes that the Näsberget magnetite-ore body is a pneumatolytic excretion of diabasic magma. The diabase occurs in dikes paralleled by perthite-bearing monzonitic and syenitic rocks, into which the diabase *merges*. The syenites and the ore are stated to be two phases of the same process of differentiation. The pneumatolytic origin is specially indicated by the development of tourmaline in the ore.[2] Heim has interpreted the kaersutite syenite of Karsuarsuk, Greenland, as formed under conditions largely pneumatolytic[3] (Fig. 180).

Further, the eclectic theory implies that the differentiation of a syenitic magma itself is progressive. The upper phase in its chamber

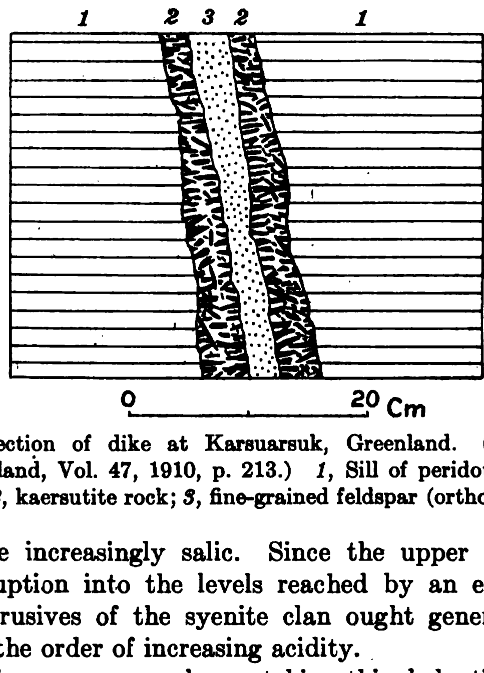

FIG. 180.—Section of dike at Karsuarsuk, Greenland. (After A. Heim, Medd. om Grönland, Vol. 47, 1910, p. 213.) *1*, Sill of peridotite bearing large augite crystals; *2*, kaersutite rock; *3*, fine-grained feldspar (orthoclase?) rock.

should become increasingly salic. Since the upper phase is more capable of eruption into the levels reached by an erosion surface, syngenetic intrusives of the syenite clan ought generally to follow each other in the order of increasing acidity.

A few of the many examples matching this deduction will suffice. Pirsson found that the monzonite of Yogo Peak stock, Montana, is cut by many dikes of banatitic syenite and quartz syenite porphyry.[4] The syenite of Rigaud Mountain, Quebec, like that at Grenville, Quebec, is cut by more salic syenite porphyry and by quartz syenite porphyry.[5] The monzonite porphyry of the Breckenridge district,

[1] W. J. Miller, Science, Vol. 36, 1912, p. 490.
[2] P. Geijer, Geol. För. Stockholm Förh., Vol. 33, 1911, p. 28.
[3] A. Heim, Meddelelser om Grönland, Vol. 47, 1910, p. 219.
[4] L. V. Pirsson, 20th Ann. Rep., U. S. Geol. Survey, Pt. 3, 1900, pp. 494, 504.
[5] O. E. Le Roy, Bull. Geol. Soc. America, Vol. 12, 1901, p. 377.

Colorado, is cut by quartz monzonite porphyry.[1] The syenite stock of Mount Ascutney, Vermont, is cut by a stock of consanguineous alkaline granite as well as by its own quartzose aplites (Fig. 64). The nordmarkite of Shefford Mountain, Quebec, cuts pulaskite and still older essexite (Fig. 181).

Statistics of Field Associations.—In general, a sedimentary formation is more extensive than the intrusive mass by which it is cut. Hence the preferred explanation implies that most of the igneous bodies from which these rocks have been differentiated should still be in contact with sediments of the right composition. The long table in

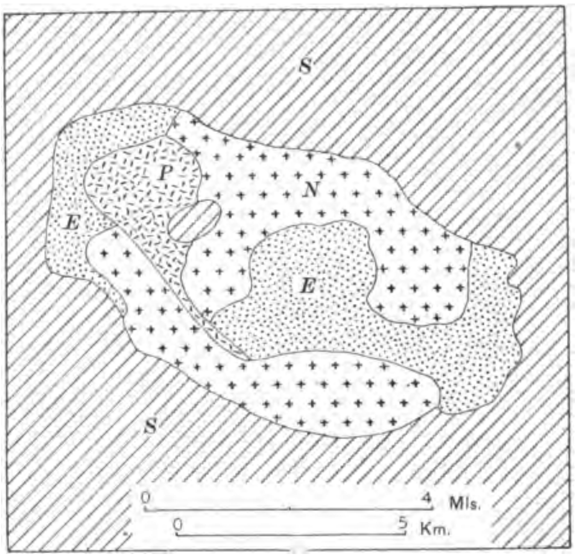

FIG. 181.—Map of Mt. Shefford, Quebec. (After J. A. Dresser, Ann. Rep. Geol. Surv. Canada, Vol. 13, 1902, Pt. L.) *S*, Lower Paleozoic sediments (argillites, etc.); *E*, essexite; *P*, pulaskite; *N*, nordmarkite.

Appendix C contains a summary statement of the way in which the records tend to substantiate this corollary of the eclectic theory. The table is not absolutely complete, but it includes references to the best known rock bodies belonging to the syenite clan. These bodies are grouped by districts of very different areas. Some of the regions cited contain only one igneous mass. Others contain many distinct bodies which, however, for each region usually show similar relations to sediments. The third column shows the nature of the invaded sediments, either directly observed in contact with the igneous masses, or inferred from the structural geology as occurring in depth. In

[1] F. L. Ransome, Prof. Paper No. 75, U. S. Geol. Survey, 1911, p. 71.

many, perhaps most, instances, the list of sediments in contact could be notably extended by more detailed study of each region. Sometimes basic igneous formations are also listed, since their solution also might exert desilicating effect on batholithic magma.

In 328 regions or 77 per cent. of all those listed in the table (426), the rule connecting basic sediments with species of the syenite clan is followed. Sufficiently complete, published data have not been found for 92 regions. Special importance must obviously be assigned to the 6 regions (1.4 per cent. of the total number) where syenitic or trachytic magma seems never to have contacted with older "desilicating" formations.

At first sight, the last-mentioned cases would appear to negative the proposed hypothesis of origins. It must be remembered, however, that several possibilities must be excluded before the negative is final. (1) The stoping of sedimentary roof rocks may have supplied the appropriate material and afterward prolonged erosion may have removed the corresponding roof formations, leaving granite, orthogneiss, or other acid wall-rocks in the existing outcrop. (2) It is conceivable that in the depths of a solidified granite batholith are large masses of sediments stoped down during the last moments of its magmatic life when the magma was incapable of assimilating the foreign material. An abyssal wedge later injected through the sunken masses and the granite alike may be chemically affected by both kinds of material. (3) In each case the possibility should be initially considered that the acid country-rock is merely a sill or laccolith resting on sediments. This relation is very often illustrated in the well exposed, pre-Cambrian, typical granites of southern British Columbia. (4) Lastly, the visible sills and laccoliths prove that magmas migrate horizontally, often for distances of scores of miles. This process should control syntectics as well as primary basalt or differentiates. Under certain conditions, a sedimentary syntectic may be moved a long distance laterally from the site of its parent abyssal wedge and injected through a terrane containing no basic sediments or basic volcanic materials. There is herein a possible explanation of the alkaline syenites of the Cripple Creek district of Colorado, which were intruded *after* the vast geanticline of the Colorado Front Ranges was updomed, with necessary disturbance of subterranean magmas. It is not incredible that the Cripple Creek rocks are differentiates of sedimentary syntectics generated in abyssal wedges even as distant as those where the Tertiary magmas of the Leadville, Breckenridge, and Georgetown districts originated.

Seeing, therefore, that the eclectic theory is supported by the facts known about the great majority of the syenite-trachyte regions, and that there are several possible explanations of the apparent failure of a few regions to support the theory, the writer is inclined to believe in a sedimentary control as dominant in the making of syenites and their chemical allies. The differentiation of these and other magmas rich in alkalies may conceivably be due, in a few instances, to transfer by juvenile gases locally and exceptionally concentrated in subalkaline magma; but it is in general simplest to regard resurgent gases as more efficient in producing the actual results.

A blanket objection to the whole conception of sedimentary control over magmas is conceivable. All of the ocean basins and most of the continental plateaus are veneered with sediments. Hence the table of Appendix C might be interpreted as involving no greater degree of association between sediments and syenites, etc., than that necessitated by the fact that these eruptives *must* usually penetrate sedimentary rocks. This view, plausible on the surface, is certainly not a satisfactory explanation. There are broad non-sedimentary areas of the continents showing very numerous igneous eruptions on the small scale and on the grand scale; yet, with extremely rare exceptions, these igneous bodies belong neither to the syenite clan nor to the other alkaline clans. The older pre-Cambrian eruptives of each continent—bodies to be numbered by the million—are characteristically subalkaline and they occur in extensive regions almost devoid of basic sediments of greater age than the eruptives.

The world's granite and granodiorite batholiths generally are cut by subalkaline dikes, stocks, etc., but rarely by syenite or other alkaline bodies. The acid crystalline-schist terranes, of whatever origin, are rarely cut by bodies of the alkaline type, though literally countless dikes and other intrusives of diabase, common granite, porphyrite, etc., are to be found.

Plentiful examples are in hand, showing adjacent sediment-free and sediment-laden areas, which respectively carry subalkaline and syenitic or other alkaline eruptives of nearly the same age.

The consecutive Montana quadrangles, mapped in the Fort Benton, Little Belt Mountains, Livingston, and Yellowstone Park folios of the United States Geological Survey, cover two such provinces. In the Fort Benton and Little Belt Mountains quadrangles and northern half of the Livingston quadrangle, the Tertiary eruptives (stocks, laccoliths, sills and dikes) include monzonite, theralite, shonkinite, syenite, etc., cutting thick Paleozoic argillites and limestones. South of Livingston, over a very extensive area, the Paleozoic cover had been largely denuded before most of the Tertiary eruptions there occurred; these afforded rock species of the subalkaline type—basalts, various andesites, rhyolites, gabbros, diorites, etc.

The many Tertiary eruptions in the California Sierra Nevada are characteristically subalkaline (basalts, andesites or rhyolites, porphyrites, etc.) where they cut the great granodiorite batholiths; the mapped latites of the range all seem to have issued in areas underlain by thick basic sediments of Mesozoic or Paleozoic age.

The great "Laurentian" batholiths of Canada are mostly subalkaline, but they often become alkaline (syenites or nephelite syenites) where they cut thick masses of limestone.

Fennoscandia is another extensive field poor in sediments but dominated by subalkaline eruptives. These are replaced only locally by alkaline types, which are generally associated with likewise local, thick masses of older, basic sediments or volcanics.

Differentiation of Syntectics in Place.—Again special attention must be given to the thick intrusive sheets or laccoliths which, having large volume and heat supply, should occasionally be capable of moderate assimilation of intruded basic sediments. Such cases are rare but they are unique in furnishing floored and roofed chambers where magmatic processes can be best understood. It is, therefore, highly significant that the differentiates of a few sheets, cutting dominant argillites and other relatively basic terrânes, differ from those of the Purcell, Minnesota, and Sudbury sheets in exactly the sense demanded by the eclectic theory.

Noble has described, unfortunately without all desired details, a great sill, cutting the argillites, sandstones, and limestones of the Unkar group (Shinumo area) at the Grand Canyon, Arizona.[1] The sill varies from 650 to 950 feet in thickness. It is chiefly composed of a typical olivine diabase.

"For about a half-mile east and west of the Shinumo there occurs in the upper part of the diabase sill along the upper contact a pink holocrystalline rock of medium grain. The contact of this rock with the overlying blue slates is sharp and well-defined. Downward it appears to grade into the normal diabase, and no definite line of contact can anywhere be observed. Unfortunately the writer did not collect transition specimens, but took only one specimen from the middle of the pink mass. The slide from this specimen when examined under the microscope showed it to be a granular rock of medium texture, consisting of rather fresh crystals of orthoclase, with subordinate quartz and a somewhat altered ferromagnesian mineral which was made out to have been originally a hornblende. Some of the quartz displayed a micrographic arrangement within the feldspar. The rock is a typical hornblende-syenite, and is apparently an interesting example of differentiation in place within the diabase sill. But a more complete set of specimens across the apparent transition zone must be collected before such a conclusion can definitely be established."

[1] L. F. Noble, Amer. Jour. Science, Vol. 29, 1910, p. 517.

Noble refers to a parallel described by Ransome in the Globe district of Arizona. The diabase here occurs as thick sills and large irregular masses cutting slaty and sericitic schists, thick shales, quartzites, and limestone.

"Within most of the larger diabase areas occur occasional masses of a reddish, usually rather coarsely crystalline rock, consisting of red feldspar, ragged prisms of ragged amphibole, and a little iron ore. The rock disintegrates readily, and its field relation to the normal diabase is not easily made out, although it seems to occur as segregations from the diabasic magma. Under the microscope the rock is rather decomposed, but it is seen that the dominant feldspar is turbid orthoclase or microline, associated with a smaller amount of plagioclase, partly chloritized and epidotized amphibole, and a little quartz in micropegmatitic intergrowths with the orthoclase. The rock is in fact a hornblende-syenite, carrying a little quartz, and its composition casts some doubt upon the hypothesis entertained in the field that it is merely a local facies of the diabase."[1]

Similarly, when the intrusive sheets of Minnesota cut dominant argillites they are sometimes charged with syenitic "red rock." As in the Shinumo sill and in the Duluth gabbro laccolith, these syenites are specially developed at or near the *upper* contacts of the intrusive bodies.

Since the syenites and their allies, like the granites, are obvious differentiates, and since differentiation almost always follows assimilation, we cannot often expect to see direct proofs of the solution of country rocks at visible contacts. However, Bastin and Hill hold that the monzonitic magma of Gilpin County, Colorado, has absorbed its (calcareous) wall rock.[2] Quensel has recently suggested that alkaline rocks studied in southern Patagonia may have been derived from sedimentary syntectics.[3] Barrell postulates an assimilation of basic sediments by andesitic magma in the Elkhorn district, Montana, where syenite and quartz monzonite have been actually differentiated after andesitic eruption.[4] It is significant that the andesites are latitic! Miller concludes that certain syenites of the Adirondack region, New York, are due to a syntexis of gabbroid magma with the Grenville gneiss-sediment series.[5]

Considering the rarity of the conditions, we must regard these

[1] F. L. Ransome, Geology of the Globe Copper District, Arizona, Prof. Paper No. 12, U. S. Geol. Survey, 1903, p. 85.

[2] E. S. Bastin and J. M. Hill, Econ. Geol., Vol. 6, 1911, p. 465.

[3] P. D. Quensel, Bull. Geol. Inst. Upsala, Vol. 11, 1911, p. 112.

[4] J. Barrell, 22d Ann. Rep., U. S. Geol. Survey, Pt. 2, 1901, p. 525–526.

[5] W. J. Miller, Jour. Geology, Vol. 21, 1913, p. 178.

instances as highly significant. The *repeated* associations of basaltic magma, basic sediments, and syenitic differentiates cannot well be accidental.

Though the Kiruna syenites of Sweden are not in visible relation to basic sediments (covered by igneous rocks or eroded away?), they seem to illustrate the gravitative differentiation of syenitic magma in place. The more ferric syenite is overlain by the more salic syenite porphyry forming part of the same eruptive body. (See pages 397 and 453.) The scanty data regarding the Beaver Creek laccolith of the Bearpaw Mountains, Montana, lead to the suspicion that the quartz syenite, monzonite, and shonkinite composing it are differentiates in place, but the mechanism of the splitting is not yet worked out.[1]

Small Size of Bodies Belonging to the Syenite Clan

The eclectic theory implies that every body of rock belonging to the syenite clan should be of comparatively small volume. When formed in a volcanic vent, which is always narrow, a sedimentary syntectic (and *a fortiori* its differentiate) cannot attain very large volume. First, the initial heat supply is small; secondly, sediments form the wall rocks of abyssal wedges only for a limited depth from the earth's surface. If, on the other hand, the assimilation takes place in a very wide abyssal wedge, there may be a much larger supply of heat, but the mixture of "acid-shell" material in depth is there likely to be carried further. Hence, flows of trachyte or latite should always be relatively small and syenitic batholiths rare.

How closely these deductions are matched by the facts is evident in the statistics of Chapter III. Extensive fissure-eruption fields of trachyte or latite are unknown. The larger known bodies of syenite, or of monzonite, while very few in number, are insignificant when compared with a first-class granite batholith.

A good case is to be found in the contrast between the huge quartz monzonite-granite Boulder batholith of Montana and the very small (probably satellitic) bodies of syenite in the adjacent Elkhorn district. The batholith cuts basic sediments and pre-Cambrian acid gneisses as well. Its differentiation has developed a quartzose rock. The relatively minute volumes of magma splitting with the syenitic pole were largely enclosed in argillaceous limestones which could locally dominate a syntectic in a *small* chamber.[2]

[1] W. H. Weed and L. V. Pirsson, Amer. Jour. Science, Vol. 1, 1896, p. 361.

[2] W. H. Weed and J. Barrell, 22d Ann. Rep., U. S. Geol. Survey, Pt. 2, 1901, p. 518.

CHEMICAL CONTRAST OF PLUTONICS AND EFFUSIVES OF THE CLAN

The various members of the syenite clan illustrate again and again the usual contrasts between the plutonic and volcanic phases of the same magma. Columns 16, 17, 18, 19, 24, 25, 28, 29, 30, and 31 in Table II give average analyses for the corresponding pairs. (See pages 229 and 401.)

The different pairs, excepting that calculated for the rare laurvikites, tell the usual story. Gravitative differentiation and gaseous transfer together must be held responsible for the more salic nature of the effusive types. The comparison thus strengthens faith in the mechanism whereby these highly feldspathic, alkaline rocks have been derived from basaltic syntectics.

CHAPTER XX

ALKALINE CLANS

Included Species

Of the ten families of plutonic rocks recognized by Rosenbusch, five will be discussed together, in their relation to the eclectic theory of origins. They are: (1) the family of the nephelite (eleolite) syenites and leucite syenites; (2) the family of the essexites; (3) the family of the shonkinites and theralites; (4) the family of the missourites and fergusites; and (5) the family of the ijolites and bekinkinites. In general these rocks, and their dike and extrusive equivalents or differentiates, are rich in alkalies or have been immediately derived from magmas rich in alkalies. The whole group, comprising nearly 200 named species or about one-third of the species named in Rosenbusch's hand-book, may be conveniently called the "alkaline" clans.

Rosenbusch and other leaders in petrography have, of course, used the term "alkaline suite" not as a chemical description of every rock species included in this suite, but rather to emphasize the syngenesis of the whole group, in which leading types are literally rich in alkalies. Other types, like limburgite, nephelite basalt, melilite basalt, basanite, or tephrite, are not absolutely rich in soda and potash, but they are so often and so closely associated with phonolites, etc. that one cannot doubt a genetic connection. A few authors have recently criticized the use of the term and have indicated the danger of confusion in the minds of immature students who do not realize that it is used symbolically by Rosenbusch and others. However, its use is likely to continue until a better one is invented to emphasize the syngenesis mentioned, which is one of the most vital facts in petrology. The name "alkaline clans" is not altogether happy for present use, since some highly alkaline types have been grouped with the granites. The syenite clan itself may be regarded as belonging to the "alkaline" group, but, on account of its importance, it has been separately treated. Though incapable of precise definition, the designation, "alkaline clans," will do no harm if it be remembered that it is here used merely as the most available, brief name for a great syngenetic group of rock families.

On the other hand, it is likewise clear that alkaline and subalkaline species are very often associated in origin—a fact matching an obvious implication of the eclectic theory. Illustrations from the petrographic record are given in this chapter.

The five clans now to be reviewed include the species named in Rosenbusch's hand-book, as follows:

Plutonic Types

1. Nephelite syenite, eleolite syenite.
   Foyaite, pyroxene foyaite, biotite foyaite, amphibole foyaite, miascite, litchfieldite, mariupolite.
   Cancrinite syenite.
   Catapleiite syenite.
   Eudialyte syenite, lujavrite, chibinite, kakortokite.
   Urtite, monmouthite.
   Sodalite syenite, tavite, naujaite.
   Leucite syenite, borolanite.
2. Essexite.
3. Shonkinite, leucite shonkinite, mica shonkinite.
   Malignite.
   Theralite, analcite diabase.
4. Missourite.
   Fergusite.
5. Ijolite.
   Bekinkinite.

Dike Types

Foyaite porphyries, eleolite-garnet porphyry, eleolite felsite, cancrinite porphyry, liebnerite porphyry, lujavrite porphyry, leucite porphyry, borolanite porphyry.
Foyaite aplite, essexite aplite, alkali aplite, paisanite, dahamite, lestivarite, heumite.
Bostonite, bostonite porphyry, lindöite, gautëite, maenaite, sodalite bostonite, sodalite gautëite.
Tinguaite, quartz tinguaite, grorudites, leucite tinguaite, sölvsbergite, allochetite.
Camptonite.
Monchiquite, fourchite, ouachitite, farrisite, mondhaldeite.
Nephelite minette, soda minette.
Alnöite.

Effusive Types

Phonolite, hyalophonolite, apachite, leucite phonolite.
Leucitophyre.

Trachydolerite, kulaite, mugearite, essexite melaphyre.
Absarokite, shoshonite, banakite.
Tephrite, leucite tephrite, haüynite tephrite, sodalite tephrite.
Basanite, leucite basanite, haüynite basanite, buchonite, basantoid, tephritoid.
Leucitite, leucite basalt.
Nephelinite, nephelite dolerite, leucite nephelinite, melilite nephelinite.
Haüynophyre.
Nephelite basalt, haüynite basalt, nephelinitoid, eudialyte-nephelite basalt.
Melilite basalt.
Limburgite, magma basalt, rizzonite.
Augitite.
Verite, fortunite, jumillite.
Orendite, wyomingite, madupite, prowersite.
Euktolite, coppaelite.
Sanukite (boninite).

General Statement of Origin

As noted in Chapter III, the alkaline rocks have been regarded by some as constituting an "Atlantic branch." It is becoming increasingly clear, however, that alkaline rocks are not confined to the Atlantic region of the globe, nor to the "Atlantic type of coastline." In 1896 Harker suggested that alkaline rocks are locally differentiated where the earth's crust has been subjected to one type of mechanical stress, namely, that which specially affected the North Atlantic basin in Tertiary time. In order to account for alkaline rocks in the Pacific basin, Harker holds that "an Atlantic as well as a Pacific element of structure enters into some parts of the Pacific basin." He further admits that even in Great Britain, one of the two Atlantic provinces where the hypothesis was first imagined, the Pacific branch is represented in all six of the known eruptive epochs (Pre-Cambrian to Tertiary), while the Atlantic branch is represented in only four. In Great Britain, Atlantic types are of Ordovician, Lower Carboniferous, Upper Carboniferous, Permian, and possibly Devonian age; but Pacific types of these dates are also plentiful.[1] Since this region is taken by Suess to typify the Atlantic type of crustal movement—Tertiary fault-blocking and foundering—it is significant that the Tertiary British eruptives are referred by Harker

[1] A. Harker, The Natural History of the Igneous Rocks, New York, 1909, p. 105.

to the Pacific branch. Similarly, the Tertiary eruptives associated with the very extensive regions of normal faulting and subsidence, in Iceland, the West Indies, the plateaus and Great Basin of Western United States, etc., are chiefly or wholly of subalkaline, "Pacific" types.

Hence, neither in Tertiary time nor in pre-Tertiary time has the Atlantic region been characterized by dominant alkaline types. On the other hand, the "Atlantic" type of crustal structure is generally accompanied by dominant subalkaline eruptives. Used even in a metaphorical sense, the new terms are misleading. Perhaps owing to a recognition of this fact, Harker prefers, in his latest publication on the subject, to describe the two branches as "alkaline" and "calcic."[1] On a following page will be found an attempt at explaining the phenomena which have prompted the Harker-Becke speculation.

Rosenbusch has concluded that monzonite and essexite (both commonly regarded as alkaline types) represent the purest undifferentiated form of the telluric magma.[2] His published statement probably refers only to specially basic monzonite, since average monzonite shows strong chemical contrast with average or typical essexite. (See Table II, Cols. 30 and 75.) Neither of these averages nor their mean corresponds to the highly probable average for all igneous rocks, reckoned quantitatively. This must approximate a true diorite or a yet more acid type, if the calculation is to include only that shell of the earth of which we have actual knowledge. (See page 168.) No other quantitative criterion has been applied by Rosenbusch and the brevity of his statement makes it difficult to see the grounds for his conclusion, which is still lacking in cogent geological evidence. If it were true, this conclusion and the associated pure-differentiation theory, would seem to imply a differentiation of granite, granodiorite, diorite, gabbro, basalt, etc., from an original magma which itself is "alkaline" and, where visible, has been usually associated with magma very rich in alkalies. The logical deduction would be that subalkaline and alkaline rocks are not derivatives of two magmas distinct "from the foundation of the world," but are syngenetic.

Chapter III (page 49) states the primary fact that the alkaline rocks have together but a very minute volume when compared with the species belonging to the gabbro, granodiorite, or granite clans. It is likewise significant that the largest known body of alkaline rock is very much smaller than the largest known body of basalt, granodio-

[1] A. Harker, Presidential Address, Geol. Sect., British Association for the Advancement of Science, 1911, p. 4 (reprint pagination).

[2] H. Rosenbusch, Mikroskopische Physiographie der Massigen Gesteine, 4te Aufl., Stuttgart, 1907, pp. 142 and 395.

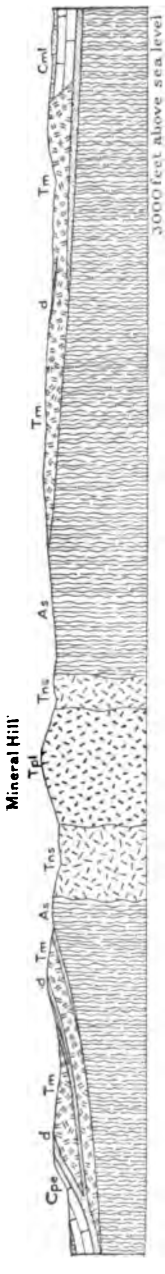

FIG. 182.—Section through Nigger Hill laccolith, Wyoming. (After Sundance Folio, No. 127, U. S. G. S., 1905.) *As*, mica schist; *d*, Cambrian; *Cpe* and *Cml*, Carboniferous; *Tm*, monzonite and syenite porphyries; *Tns*, nephelite syenite; *Tpl*, pseudoleucite porphyry. Illustrating intimate relations between members of the syenite and "alkaline" clans. Horizontal and vertical scales, 1:73,000.

rite, or granite. Fig. 194 shows the comparatively minute volumes of classic phonolites. These facts directly suggest the wisdom of closely examining the hypothesis that the alkaline rocks are derivatives of the spectacularly abundant magmas. The evidence summarized in this chapter is additional to that detailed in Chapter XIX; its strength is such that the writer favors the hypothesis. For this and other reasons he prefers "subalkaline" to "calcic" as a general designation for the rocks relatively poor in alkalies. The former term signalizes the fact that the common magmas carry alkalies which by concentration rise to the proportions characterizing a foyaite, an urtite, or a leucitite.

The very frequent association of nephelite syenites, leucitic rocks, essexites, shonkinites, etc., with ordinary syenite or monzonite indicates a common mode of origin for all these families (Figs. 182–4). The question whether the alkaline clans have also been differentiated from sedimentary syntectics has already been attacked by the writer and the result has been published.[1] It was concluded that most of the "alkaline rock" bodies originated in syntectics of basalt with carbonate-bearing rocks, limestones, dolomites, marls, or other calcareous or magnesian sediments. The line of thought is, on the whole, parallel to that adopted in the last chapter. Some of the principles need not be fully restated.

A glance at a few *a priori* arguments will aid in quantitatively estimating the problem.

In the first place, fluid basaltic magma, with superheat of the order actually observed at Kilauea, Matavanu, or Etna, *must* absorb limestone in direct contact with it. Koenigsberger and Müller have shown that in water solutions silicic acid is stronger than carbonic acid at as low a temperature as 260° C [2]. These acids certainly have

[1] R. A. Daly, Bull. Geol. Soc. America, Vol. 21, 1910, pp. 87–118.

[2] J. Koenigsberger and J. Müller, Centralbl. für Miner. etc., 1906, pp. 339 and 353.

the same relation in natural magmas, as shown by the abundant development of lime silicates at contact of limestone and intrusive rock. According to Cobb, dry lime and silica begin to react at 800°.C., a temperature far below that of most basaltic magmas at eruption.[1] The igneous rocks of Colonsay and Oronsay (Hebrides islands) include both alkaline and subalkaline types. The intrusives carry xenoliths of quartzite, which have suffered partial assimilation.[2] Is it possible to doubt that the same magmas could also absorb the Torridonian limestones and phyllites likewise invaded? Reinisch holds that the high silica of the leucite basalt of the Gaussberg, Antarctica, is due to the assimilation of granite and gneiss xenoliths.[3] It is logical to suppose that the basalt, at the same temperature, could have assimilated carbonate rocks.

Hibsch concluded that the great diversity of magmas in the "alkaline" province of Bohemia is best explained by the magmatic assimilation of different rock materials; but he has offered no discussion of the chemical processes involved.[4]

Carbonate rocks are evidently more prone to upset chemical equilibrium in basaltic magma than is any other large-scale formation which can be absorbed by it.

This implies, secondly, that differentiates of the basalt-limestone syntectic will be more varied in composition than the differentiates of other syntectics. The great diversity of types in the alkaline clans is of the order of magnitude demanded on the proposed hypothesis.

Thirdly, the conditions under which carbonate rocks can be easily assimilated by eruptive magmas are special and local, and those conditions under which the influence of the absorbed limestone is not masked by that of gneisses or other acid rocks simultaneously dissolved are yet more exceptional. The comparative rarity of alkaline rocks is also of the same order as that characterizing the geological conditions which favor the absorption of dominant limestone in subalkaline magma. The points of eruption on the earth for basaltic or gabbroid magma should be incomparably more abundant than those for alkaline magmas—an obvious fact.

Association with Carbonate Rocks.—Rocks belonging to the alkaline clans are recorded in the regions listed in Appendix D, where will be found the names of nearly all the important localities where

[1] J. W. Cobb, Jour. Soc. Chem. Industry, Yorkshire Section, Vol. 29, 1910, Nos. 2, 5, 6, 7, and 10.

[2] Craig, Wright, Bailey, Clough and Flett, Memoir 35, Geol. Survey of Scotland, 1911.

[3] Cf. E. Philippi, Deutsche Südpolar Expedition, 1901-1903, Berlin, 1906, Bd. 2, Heft 1, p. 54.

[4] J. E. Hibsch, Tschermak's Min. Petr. Mitt., Vol. 12, 1892, p. 405.

alkaline rocks have been discovered. Partly because of the pure-differentiation theory of igneous rocks which has so flagrantly ignored the possibility of assimilation, many authors have furnished little or no information regarding the terranes invaded by the "interesting" alkaline rocks. It needs no emphasis that the districts named are exceedingly variable in area. One may be listed because it carries a single dike of alkaline rock; another is named as of the same category though it really represents an extensive province covering hundreds

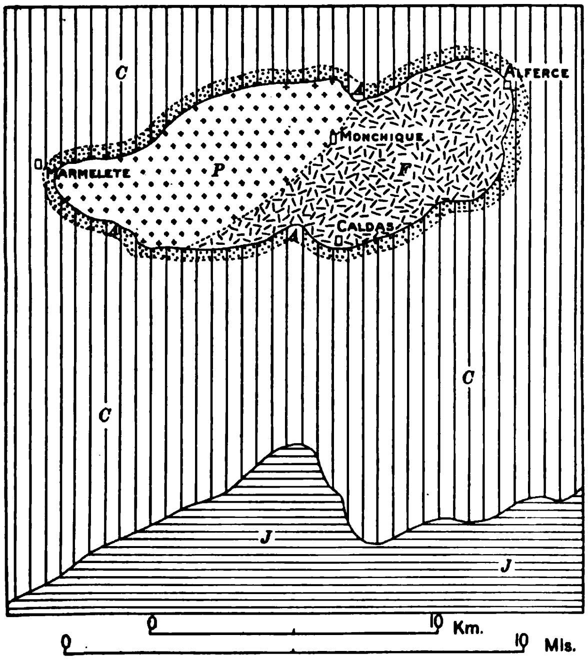

FIG. 183.—Map of the Monchique intrusion, Portugal. (After K. von Kraatz and V. Hackman, Tscher. Min. Petr. Mitt., Vol. 16, 1896, and Government map of Portugal.) *C*, Carboniferous slate and graywacke; *J*, Jurassic limestone (chiefly); *A*, metamorphic aureole; *F*, foyaite; *P*, pulaskite.

of alkaline bodies. To be thoroughly useful, such a table should be quantitative and indicate the volumetric importance of each species in each district. The ideal cannot be closely approached until much more field work is done, but the tables, as they stand, have considerable value in petrogenic theory. A more detailed statistic would yet more clearly substantiate the following conclusions.

In all, 234 districts are known to contain alkaline eruptives. Of these, 163 districts, or 70 per cent., show these types to be associated with carbonate rocks in the way required on the proposed hypothesis.

In constructing the tables, it was often necessary to search for information as to the sedimentary terranes underlying the present land surface in the districts. Care was taken to assume limestone below the surface only when the facts pointed strongly in that direction. It was sometimes clear, too, that limestones were present in the roofs of alkaline intrusives of the stock or batholith order, and it was then legitimate to consider such limestone as subject to stoping and abyssal assimilation during intrusion. For example, the large body of foyaite in the Foya district of Portugal is mapped as in direct contact with Devonian graywacke, slate, and sandstone. The region has been greatly denuded since it was wholly covered by thick Jurassic limestone and other sediments[1] (Fig. 183). Is it possible that the original roof-rock of the Foya intrusive was partly limestone, which affected the magma through stoping and deep-seated solution? The co-operation of pre-Devonian limestones is, of course, not excluded.

Information as to the nature of the country rocks is lacking in 63 districts, largely volcanic islands, which, however, are likely to have limestones in their foundations.

In only 8, or 3.4 per cent., of the districts are alkaline rocks apparently in such relations that the local absorption of carbonate rocks is impossible. Few as these regions are, they are of obvious concern to the hypothesis, and it is expedient to survey the facts in detail.

Though an advocate of large-scale assimilation by magmas, Ussing considered that the nephelite syenites of Julianehaab, Greenland, cannot be explained as differentiates of carbonate syntectics. He wrote: "The complete absence of carbonate-rocks in the whole country around the very large nepheline-syenite areas of south Greenland is inconsistent with the hypothesis recently set forth by Daly relating to a genetic connection between carbonate-rocks and nepheline-syenites (Origin of the Alkaline Rocks, Bull. Geol. Soc. of America, XXI, p. 87, 1910). The only carbonate-bearing formation of South Greenland is the Arsuk group (p. 9). The possibility that dolomites of this group have once existed at Julianehaab cannot be denied. But the late-Algonkian igneous series (Julianehaab granite, etc.) which is later than the Arsuk group consists of sub-alkaline rocks. Thus, actual observations tell against the hypothesis in every way."[2]

The Greenland case somewhat resembles that at Cripple Creek, Colorado, where nephelite syenite and phonolite have been erupted through batholithic granite.

Since the general statistics of the Appendix tables so strongly favor the idea of sedimentary control, the writer is impelled to risk

[1] Cf. C. P. Sheibner, Quart. Jour. Geol. Soc., Vol. 35, 1879, p. 42.

[2] N. V. Ussing, Meddelelser om Grönland, Vol. 38, 1911, p. 297, footnote.

the charge of special pleading and to point out several possibilities in these and similar instances.

As an independent author of the stoping hypothesis, Ussing presumably would have applied it as explaining the emplacement of the Julianehaab granite, through which these Greenland foyaites, etc., were intruded. Since the granite is younger than the calcareous Arsuk group, it is possible that carbonatic matter was sunk into the granite batholith in the late-magmatic condition when it was unable to absorb all of the foreign material, or to permit advanced diffusion of that material after its assimilation. A later superheated basaltic wedge, penetrating such a mass abnormally rich in lime or carbon dioxide, would necessarily be chemically affected.

Again, these few cases are subject to the possibility that the alkaline rocks represent magmas which have migrated laterally from their original "hearths"—a conception emphasized, for other purposes, by Harker, who applies it on a wholesale scale.[1] (See page 404.) While carbonate-rocks are unknown in the immediate vicinity of Julianehaab, the country rocks are completely hidden by the great ice-cap east of the alkaline Igaliko mass. The Arsuk group or other calcareous formations may be liberally represented in that region; they may have entered into a syntectic at a considerable distance and then have migrated horizontally to the Ilimausak and Igaliko chambers. These Julianehaab bodies have several features suggesting that they are not batholiths but irregular laccoliths or chonoliths.

Deep-seated migration of sedimentary syntectics is not to be excluded as a possible phase of the Cripple Creek eruptives. The Rico, Leadville, Georgetown, Breckenridge, and other districts of western Colorado (all carrying syenitic, trachytic, or monzonitic rocks) show conditions favorable to the abyssal assimilation of thick limestones. The Tertiary up-doming of the Front Range of the Rocky Mountains necessarily involved subcrustal movement of magma toward the axis of the dome. (See also page 404.) Is it rash to postulate that this magma was alkaline? Probably field proof of this and of the syntectic origin of the transported magma can never be found, but the speculation has value in forbidding dogmatic assertion that the Cripple Creek magmas are not of syntectic origin. As noted in the preliminary paper, the deeper mine workings of the Cripple Creek district are specially, seriously affected by the abundant emanation of carbonic acid gas from the igneous rocks. The gas may be of syntectic origin, or it may suggest that the foyaitic magma has been generated

[1] A. Harker, Pres. Add., Brit. Assoc. Adv. Science, Section C, 1911, p. 6, reprint.

because of an unusual concentration of *juvenile* (not resurgent) carbon dioxide beneath the Front Range dome.

Pirsson has described the nephelite syenite stock at Red Hill, New Hampshire.[1] The mass is intrusive into a granitic gneiss which surrounds it on all sides. No sediments occur in the immediate vicinity but it is known that thick calciferous formations underlie much of New Hampshire as well as Maine and Vermont. Two possibilities are open. The roof of the Red Hill stock, now eroded away, may have been partly composed of these calcareous members; or it may represent syntectic magma which has migrated from a distance. It may be noted that the trachyte, syenite, and teschenite, cutting Paleozoic

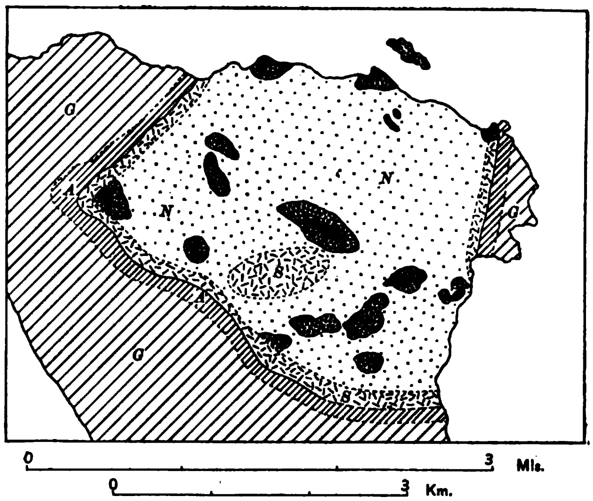

FIG. 184.—Map of part of Alnö Island. (After A. G. Högbom, Geol. Fören. Förhand., Vol. 17, 1895, Pl. 2.) *G*, Gneiss; *A*, metamorphic aureole in gneiss; *solid black*, limestone; *heavy dots*, limestone with nephelite syenite; *S*, syenite; *N*, nephelite syenite.

limestones in Aroostook County, Maine, are on the (Appalachian) strike from Red Hill.[2]

Several other areas of alkaline rocks, *e.g.*, those at Port Coldwell, Ontario, in Brazil, in Lappland, in Eastern Africa, etc., need more complete mapping before their failures to show positive evidence can be regarded as of telling moment.

On the other hand, any number of such difficult cases cannot shake one's belief, with Adams and Barlow, that the nephelite syenites of the Hastings-Haliburton area, Ontario, are genetically connected with the Grenville limestones alongside. Whatever the origin of the

[1] L. V. Pirsson, Amer. Jour. Science, Vol. 23, 1907, p. 257.

[2] See H. E. Gregory, Bull. 165, U. S. Geol. Survey, 1900, p. 93.

limestone masses at Alnö, their partial solution in nephelite syenite magma, or in that from which nephelite syenites have been derived, is an objective fact (Fig 184). Is it even conceivable that the Italian lavas have traversed the thick Mesozoic limestones and dolomites, now covered by flows and breccias, without dissolving some of the carbonate? Could the feeders of the Pilandsberg foyaitic eruptive fail to dissolve the Great Dolomite as they rose through its thousands of feet of thickness? Can one ignore the fact that the alkaline eruptives of Montana must have penetrated thick masses of calcareous sediments before reaching the observed levels? Was the Arkansas magma inert when it intruded the very thick limestones beneath the Magnet Cove region? No other question in petrogeny can be regarded as more necessary or more insistent than these and the many similar ones suggested by the list in Appendix D.

With his usual keenness, Teall saw the unavoidable nature of the question. In a paper on the alkaline eruptives of Loch Borolan, Scotland, he wrote:

"To what extent the different rocks represent successive intrusions, differentiation *in situ*, or the result of a modification in the composition of the original magma by the absorption of adjacent limestones, has not been clearly made out."

He remarked that all three processes were possibly engaged.[1]

Högbom states that the acid contact phase (alkaline syenite) of the Alnö stock is due to marginal assimilation of the invaded gneiss by nephelite-syenite magma.[2] Is it then possible to doubt that the limestone masses enclosed in the same magma must have exerted the contrary, desilicating effect on the original magma of the Alnö stock? The actual solution of the carbonate on a large scale has been thoroughly demonstrated by Högbom (Fig. 184).

The possible objection that alkaline rocks are generally associated with calcareous sediments merely because sediments of that character seldom fail on continental plateau or in ocean basin, can be answered in the same way as the analogous objection for the syenite clan has been answered. Important calcareous formations are truly lacking over vast areas of the continents, where igneous eruptions have been numerous and yet have afforded no members of the alkaline clans. A few examples will illustrate the fallacy of the objection.

The Livingston (Montana) folio of the United States Geological Survey shows that the Tertiary theralites and allied rocks of this extensive quadrangle are found only in the area underlain by thick

[1] J. J. H. Teall, Geol. Mag., Vol. 7, 1900, p. 390.

[2] A. G. Högbom, Geol. Fören. Förhand., Vol. 17, 1895, p. 132.

limestones. Elsewhere the limestones had been eroded away before the Tertiary eruptions began and these furnished only subalkaline species.

In Java and Madura the early Tertiary lavas (all subalkaline) penetrated a terrane devoid of important calcareous beds. After the thick Miocene limestone was deposited along the northern coast of Java, it was traversed by new eruptives, largely alkaline.[1]

The Paleozoic eruptives of Bohemia are all, so far as known, subalkaline—diabases, diorites, granites, etc. Only after the Tertiary limestones were deposited over the region and igneous activity renewed, were the phonolites and their allies erupted. Bohemia contains an alkaline province now but it contained none in the Paleozoic era.

Field Association with the Gabbro Clan.—The eclectic theory predicts two modes of association between alkaline rocks and the substratum material. The connection may be direct, where members

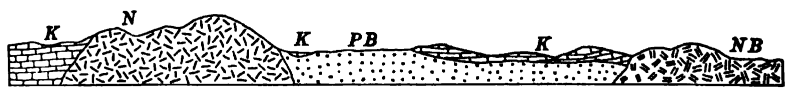

FIG. 185.—Section in the Uvalde quadrangle, Texas. (After Uvalde Folio, No. 64, U. S. G. S., 1900.) *K*, Cretaceous limestone and clay; *PB*, intrusive plagioclase basalt; *N*, intrusive nephelite-melilite basalt; *NB*, nephelite basalt. Illustrating syngenesis of ordinary basalt and "alkaline basalts." Horizontal scale, 1:95,000; vertical scale, 1:12,000.

of the gabbroid clan are clearly syngenetic with alkaline types; or indirect, where alkaline types are syngenetic with differentiates of basalt or of basaltic syntectics.

The *direct* association may be in the form of: (a) transitions; or (b) adjacent separate eruptions accomplished in the same petrogenic cycle.

Transitions from an alkaline phase to a subalkaline phase in the same rock-body seem to be very uncommon. An example is recorded in the San Luis quadrangle of California, where olivine diabase merges into augite teschenite within the limits of an intrusive sheet.[2] (See also page 339.)

The rarity of such cases is not a valid objection to the sediment-control hypothesis. The absorption of carbonate has a specially violent chemical effect on primary magma, as detailed in the following pages. Even a small amount of this absorption must flux the magma and specially induce its differentiation into submagmas varying

[1] R. D. M. Verbeek and R. Fennema, Description géologique de Java at Madoura, Amsterdam, 1896, pp. 38, etc.

[2] San Luis Folio, U. S. Geol. Survey, 1904.

from melilite basalts, nephelite basalts, and limburgites to phonolites. Hence we should not expect transition to normal basalt, diabase, or gabbro as often as in the case of members of the diorite, granodiorite, and granite clan, when derived from silicious syntectics. Melilite, leucite, and nephelite basalts are generally regarded as belonging to the alkaline series, but many of them, like quartz basalt, are only slightly modified plagioclase basalt.

Much more frequently the syngenesis of separate alkaline and basaltic or gabbroid bodies is evident. Fig. 185 shows the intimacy

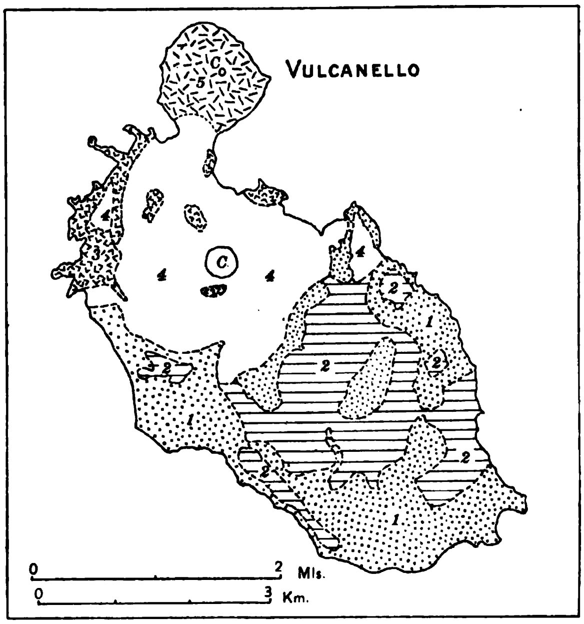

FIG. 186.—Plan of island of Vulcano. (After A. Bergeat, Abhand. k. bayer. Akad. Wiss., math.-phys. Kl., Vol. 20, 1899, Taf. 6.) *C*, Craters; *1*, basalts and basaltic andesites; *2*, basaltic agglomerates; *3*, liparites; *4*, tuffs and sands of the Fossa di Vulcano; *5*, leucite basanite. Illustrating close association of basalts, andesites, and an alkaline type.

existing between the plagioclase basalt and nephelite-melilite basalt of a very local area in the Uvalde Mountains, Texas.[1]

Figure 171 is a diagrammatic map of Stromboli, showing the generation of leucite basanite in the throat of a very young volcano which had erupted dominant basalt and pyroxene andesite.[2] Bergeat gives the order of eruption for Vulcano as: 1. Basaltic andesite. 2. Liparites. 3. Leucite basanite (of the Vulcanello) (Fig. 186). The surface

[1] Uvalde Folio, U. S. Geol. Survey, 1900, p. 5, Fig. 2.

[2] A. Bergeat, Abhand. k. bayer. Akad.Wiss., Zweite Klasse, Vol. 20, 1899, p. 27.

lavas of Etna are dominantly basaltic but they also include leucitophyres.[1] Fig. 187 illustrates another occurrence of basalts and leucitic rocks in the same cone (Roccamonfina).[2] Many analogous associations are known in Hawaii, Samoa, Tahiti, Possession Island, New Zealand (Dunedin, Figs. 188–9), Juan Fernandez Islands, Heard Island, Kerguelen, St. Helena, Ascension, Sao Thomé, Réunion, Madagascar (Fig. 190), Canary Islands, Cape Verde Islands, Azores, Madeira, Pantelleria, etc. In this connection the assemblage of lavas

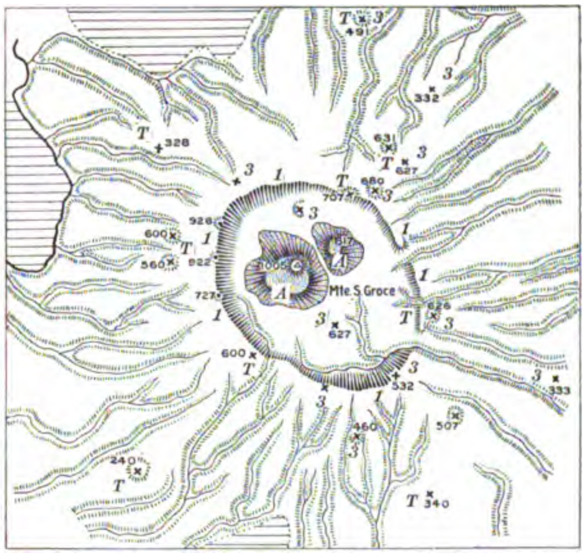

FIG. 187.—Map of Roccamonfina volcano, Italy. (After W. Kranz in Peter. Geog. Mitt., Vol. 58, März Heft, 1912.) *Cross-lining*, Mesozoic and Tertiary basement rocks; *1*, leucitites and leucite tephrites of the 1st eruptive period; *A*, augite andesites of the 2d eruptive period; *T*, Trachytes and leucitophyres of the 2d eruptive period; *3*, basalts of the 3d eruptive period. Lateral eruptions shown by crosses; altitudes in meters. Illustrating intimate association of basalt, andesite, and alkaline types. Scale, 1:215,000.

in Germany is significant. In the Lower Rhine region, plagioclase basalts (olivine-bearing and olivine-free), augite andesite, hornblende andesite, nephelite basalt, trachyte, and phonolite have been erupted during the Miocene. In the Upper Rhine region, feldspar basalts, melilite basalt, nephelite basalt, leucite-nephelite basalt, tephrite, limburgite, and phonolite date from the same period. Very similar types of lava were extruded during the Quaternary in the Lower

[1] H. J. Johnston-Lavis, Boll. soc. Ital. Microscopisti, Acireale, Vol. 1, 1889, p. 26.

[2] W. Kranz, Petermann's Mitt., Vol. 58, 1912, p. 131, Pl. 26; Cf. H. J. Johnston-Lavis, The South Italian Volcanoes, Naples, 1891, p. 26.

Rhine region.[1] The assemblages at the Mont Dore, Velay, Cantal (Fig 191), Limagne, and le Livradois (Fig. 193) volcanic centers of France, and in the Bohemian Mittelgebirge, tell the same story. In

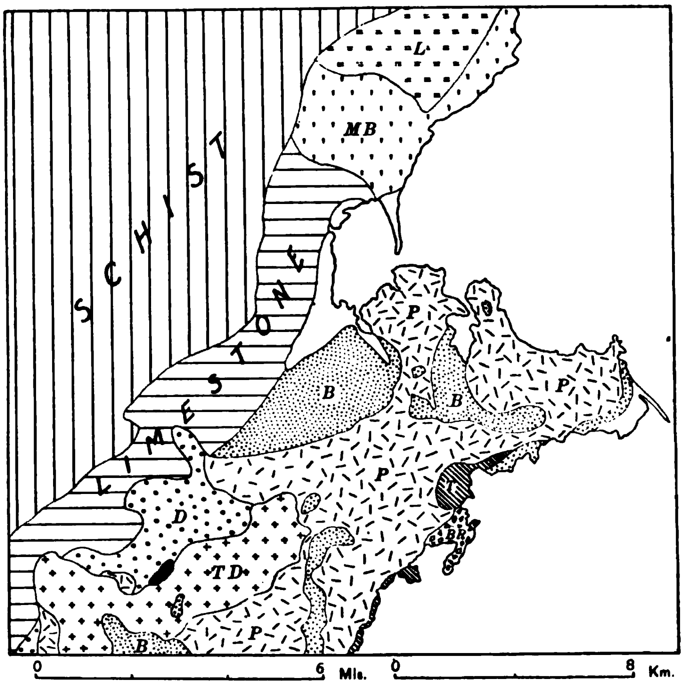

FIG. 188.—Map of part of the Dunedin district, New Zealand. (After P. Marshall, Quart. Jour. Geol. Soc., Vol. 62, 1906, Pl. 36.) *T*, Trachyte; *BR*, breccia; *P*, phonolite; *TD*, trachydolerite; *B*, basalt; *D*, dolerite; *solid black*, nephelite basanite; *L*, leucitophyre; *MB*, melilite basanite; *blank*, sand and alluvium. Illustrating close association of alkaline and subalkaline types.

each district alkaline and subalkaline rocks are not only close together; their eruptions fall within the limits of a *short* geological period.

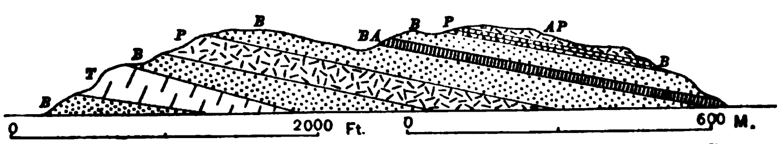

FIG. 189.—Section at North Otago Head in area of Fig. 188. (Same ref., p. 418.) *B*, basalt; *T*, trachyte; *BA*, basanite; *P*, phonolite; *AP*, andesitic phonolite.

Such repeated close associations, both in space and time, make it incredible that each set of alkaline lavas has an origin independent

[1] R. Lepsius, Geologie von Deutschland, 2er Teil, Leipzig, 1887–1910.

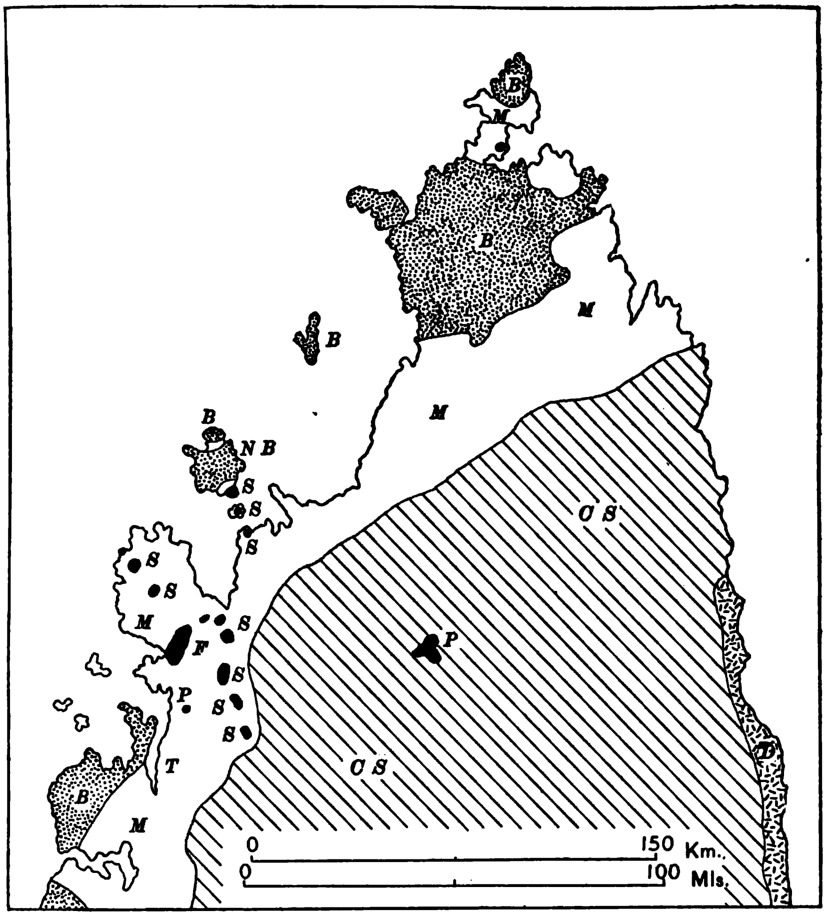

Fig. 190.—Map of northern Madagascar. (After R. Baron, Quart. Jour. Geol. Soc., Vol. 51, 1895, and P. Lemoine, Études géologiques dans le nord de Madagascar, 1906.) *CS*, crystalline schists and marbles; *M*, Jurassic and Cretaceous (largely limestone); *S*, syenite; *F*, foyaite; *P*, phonolite; *T*, trachyte; *NB*, nephelite basalt; *B*, basalt, chiefly olivine-bearing; *D*, dolerite.

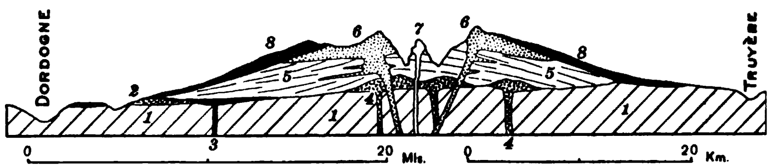

FIG. 191.—Section of the Cantal volcano, France. (After M. Boule, Guide 8e. Cong. Géol. Internat., Pt. 10, p. 9.) *1*, gneiss and mica schist; *2*, Oligocene sediments; *3*, Miocene basalt; *4*, Miocene trachyte and phonolite; *5*, Pliocene breccia and tuff; *6*, Pliocene andesite flows; *7*, Pliocene phonolite; *8*, Plateau basalt.

of that to be assigned to the accompanying basalts. Rosenbusch himself has concluded that the keratophyres, long held to be typical representatives of the alkaline series, are aplitic differentiates of subalkaline magmas.[1] He states that the keratophyric rocks are the only ones which break the rule that alkaline and subalkaline types always occur in separated areas (Verbreitungsgebiete).[2] The foregoing examples and a host of others, such as those listed in Appendix B, clearly oppose this view. It cannot be substantiated by the remark that the listed basalts, diabases, gabbros, etc., have been wrongly diagnosed. Their diagnosis is the work of many of the world's ablest petrographers. For example, Rosiwal long ago listed the many species of alkaline rocks and closely associated common feldspar basalts and pyroxene andesites found by the various expeditions which had then investigated Abyssinia and the adjacent region of East Africa.[3] Subsequent work has not invalidated but has substantiated the fact of this association of types.

The *indirect* association with basaltic magma is not less striking. The Mauna Kea center in Hawaii has recently erupted basic andesites and trachydolerites which are almost indistinguishable in the field and nearly identical in their chemical analyses. The field relations and mineralogical and chemical composition of the Hawaiian trachydolerites strongly suggest that, like the andesites, they are differentiates of the overwhelmingly dominant olivine basalt of the island. The rare phonolites of Hawaii occur in just such limited volume as that expected if the basalt had absorbed small quantities of limestone in lateral vents. In any case, these more salic types are most simply explained as special differentiates of basalt. The extremely close intimacy between andesite and an alkaline type on Mauna Kea is paralleled in many volcanic areas. Verbeek and Fennema found that the hornblende andesite of the Lourous volcano in Java had been intruded through leucitic olivine basalt. A similar basalt, together with leucitite, tephrite, and nephelinite, forms the Ringguit volcano. A few other areas of alkaline rocks are distributed among the prevailing andesites and plagioclase basalts emitted at the long Javanese fissures.[4] Rack has recently shown that the small volcanic island, Soembawa, in the same province, is built up of dacites, andesites of several types, and leucitic tephrites and basanites.[5] Short-lived, local eruptivity

[1] H. Rosenbusch, Mikroskopische Physiographie der Massigen Gesteine, 4te Aufl., Stuttgart, 1908, p. 1493.

[2] Op. cit., p. 1492.

[3] A. Rosiwal, Denkschr. Akad. Wien, Math. Nat. Kl., Vol. 58, 1891, p. 87.

[4] R. D. M. Verbeek and R. Fennema, Description géologique de Java et Madoura, Amsterdam, 1896.

[5] G. Rack, Neu. Jahrb. für Miner. etc., B.B. 34, 1912, p. 42.

during the Cretaceous period formed the layer of volcanic breccia visible at the railroad track near Blairmore, Alberta. The breccia fragments include true andesite, augite trachyte, analcite trachyte, and tinguaite. It is highly probable that all four types were generated nearly contemporaneously and in identical or neighboring vents.[1] Similarly, Lacroix found andesites, basaltic types, and leucitites in the same breccia series from Trebizond.[2]

Injected bodies give remarkable proofs that alkaline and subalkaline rocks are not confined, respectively, to separate provinces. Nothing could be more spectacular than the rock associations in the Bushveldt laccolith of the Transvaal. Molengraaff, Brouwer, Humphrey and others have shown that this colossal granite-norite-gabbro-pyroxenite injection, marvellously differentiated, is traversed by intrusive foyaites and syenites with extrusive, phonolitic and trachytic phases. Though the younger complex is 20 miles in diameter, it lies completely surrounded by the subalkaline rocks of its mighty associate.[3] (Fig. 162, page 351).

Turning to the subjacent intrusive bodies, the associations are again found to be of the kind required by the eclectic theory. According to conditions, a great abyssal wedge should locally absorb very different amounts of carbonate, argillaceous, or acid rock. The respective syntectic phases of the wedge should, by the theory, furnish differentiates of nephelite syenite, syenite, granodiorite, diorite, or granite. All these types should be developed in the same batholith or in the members of a composite, one-cycle batholith. A few examples will show how this prediction is fulfilled.

In the Yenisei district of Siberia, Meister has found a highly varied group of syenites, nephelite syenites, soda-granites, banatites, diabases, gabbros, peridotites, picrites, etc., cutting a thick series of basic schists, slates, dolomites, and limestones, the last-named having an "immense development." He writes:

"It is quite impossible to suppose that the eruption of these rocks, partly pertaining to granito-dioritic, gabbro-dioritic, and gabbro-peridotitic magmas and partly to foyaito-theralitic magma, belongs to two distinct periods. On the contrary, the foyaito-theralitic rocks alternate in age with those derived from granito-dioritic magma."[4]

[1] C. W. Knight, Canadian Record of Science, Vol. 19, 1905, p. 265.

[2] A. Lacroix, Bull. soc. géol. France, Vol. 19, 1891, p. 732.

[3] G. A. F. Molengraaff, Bull. soc. géol. France, Vol. 1, 1901, p. 13 (map); H. A. Brouwer, Oorsprong en Samenstelling der Transvaalsche Nephelien-syenieten, 's Gravenhage, 1910 (map); W. A. Humphrey, Trans. Geol. Soc. South Africa, Vol. 15, 1912, p. 100.

[4] A. Meister, Sur les Roches et les Gisements d'Or dans la Partie Sud du District d'Jenissei, St. Petersburg, 1910, p. 593.

The composite batholith of the Okanagan mountains in Washington and British Columbia affords an exceptionally well exposed, large-scale illustration (Fig. 65, p. 115). The syenites, malignites, and nephelite syenites of the Kruger body are clearly syngenetic, not only with each other but also with the granodiorite, quartz diorite and monzonite of the Similkameen intrusive, and with the alkaline granite of the still younger Cathedral body.[1]

In his important monograph on the geology of north-central

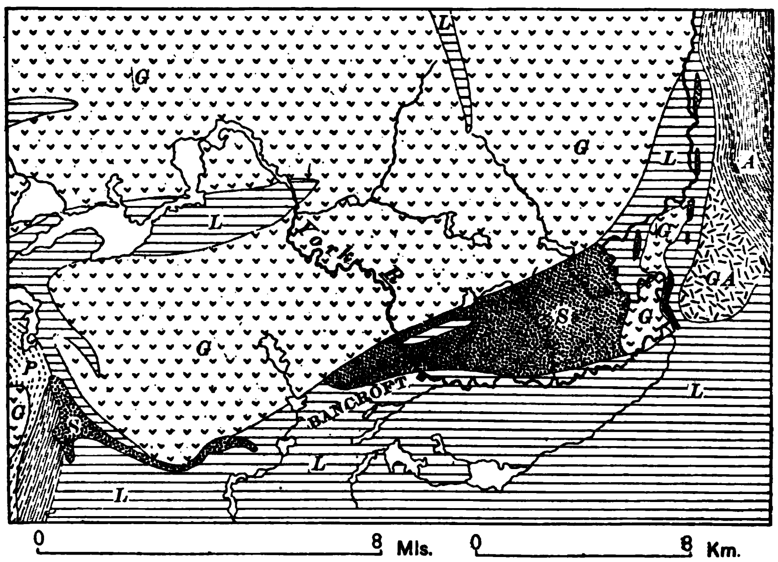

Fig. 192.—Map of the Bancroft district, Ontario. (After F. D. Adams and A. E. Barlow, Memoir 6, Geol. Surv. Canada, 1910.) *P*, paragneiss; *L*, Grenville limestone, etc.; *A*, amphibolite; *GA*, gabbro; *G*, granite and orthogneiss; *S*, nephelite syenite.

Wisconsin, Weidman points out that there the nephelite syenite, syenite, and granite are not only consanguineous but are genetically connected with somewhat older gabbros and diorites as well as with somewhat older rhyolites and andesites. He writes:

"This close correspondence in the pronounced chemical features of the three magmas [rhyolitic, gabbro-dioritic, and granite-syenitic] is not believed to be accidental or by chance, but assignable to definite causes, although the causes may not be understood. As additional evidence of relationship in origin may be cited the fact of associated occurrence and eruption in the same geological age."[2]

[1] Cf. R. A. Daly, Memoir No. 38, Geol. Surv. Canada, 1912, p. 425, and Map Sheets Nos. 12 and 13.

[2] S. Weidman, Bull. 16, Wisconsin Geol. and Nat. Hist. Survey, 1907, p. 353.

The little mass at Predazzo, containing nephelite syenite, essexite, shonkinite, theralite, syenite, quartz syenite, quartz monzonite, pyroxenite, and granite—all cutting melaphyre and olivine-bearing augite andesite—is a vivid example of the syngenesis of types belonging to all or nearly all of the igneous clans.[1]

The Haliburton-Bancroft region in Ontario offers most striking evidence favoring sedimentary control in the formation of nephelite syenites (Fig. 192). Adams and Barlow have mapped about thirty distinct areas of these rocks, occurring in fourteen townships. The authors write:

"The nepheline and associated alkali syenites are found either along the actual contact of the granite and the limestone, or in the limestone itself near the granite contact. There is only a single exception to this in the area under discussion, namely, the nepheline syenite mass in the township of Methuen, which occurs between a great granite intrusion and the body of amphibolite, containing a few small bands of limestone.

"They are intruded into the crystalline limestones and associated sedimentary rocks of the Grenville series on the one hand, and, as far as can be determined at the several points where they are well exposed, they pass over into the fundamental gneiss on the other hand. Elsewhere, however, dikes of the nepheline syenite or associated alkali syenites can be seen to cut the fundamental gneiss. A careful study of the whole area shows that the nepheline syenite and its associated alkali syenites represent a peripheral differentiation phase of the granite (fundamental gneiss), and that in the few cases where these rocks are seen to cut the fundamental gneiss they are of the nature of dikes of differentiated material intruded into a more acid phase of the same magma, which was already consolidated very much in the same way as in the case of ordinary granite pegmatite, dikes are found representing the last product of consolidation of a common magma. . . . . .

"The nepheline syenite occurs almost invariably along the border of the granite intrusions where these are protruded through the limestone. When the actual contact of the nepheline syenite and limestone can be seen, masses of the limestone, great and small, are found scattered through the nepheline syenite along the contact. These masses are in course of replacement by the magma, and at a distance from the contact are seen to be greatly reduced in size and often disintegrated. Still further from the contact they are represented by irregularly rounded grains of calcite lying between the perfectly fresh individuals of the several constituent minerals of the nepheline syenite, or in some cases actually as inclusions in these minerals. . . . . .

"The origin of the nepheline syenite so extensively developed in the Bancroft region is also, as has been shown, in some way connected with the granite intrusions. It is a differentiation phase, or a product of the magma in question, and is almost invariably associated with limestones, which are in some

[1] Compare W. Penck, Neues Jahrb. für Miner. etc., B. B. 32, 1911, p. 341; J. Romberg, Sitzungsber. Akad. Wiss. Berlin, 1902, pp. 673 and 731, and 1903, p. 43.

way genetically conneeted with it. It is worthy of note that in Professor Lacroix's area in the Pyrenees, nepheline syenite also occurs, though here in smaller amount, and under such conditions that it is impossible to determine its actual genetic relations."[1]

These foyaitic rocks occur over a very extensive region characterized by well-distributed, large injections of ordinary gabbro and by many other eruptive bodies of basaltic composition. These are generally older than the batholiths and prove the local existence of subcrustal basaltic magma before the great masses of granite were emplaced. The field relations, therefore, correspond to the basal assumptions of the eclectic theory. If the granite itself (generally a common type not specially alkaline) is a differentiate of a basaltic syntectic, the nephelite syenites of the region must have an indirect connection with the primary basalt of the substratum. In any case, the masterly investigation of Adams and Barlow illustrates the fallacy of regarding alkaline and subalkaline magmas as primordially and always separate and it most clearly suggests that large bodies of foyaitic magma are genetically connected with carbonate rocks.

It is unnecessary to detail many other illustrations, such as that of the Christiania Region or others listed in Appendix D. The reader will, of course, note that the present argument favoring the indirect and direct association of foyaitic rocks with the gabbro clan is based on the same principle as that used in the discussion of the syenite clan. The relevant facts described in the last chapter thus tend to strengthen the reasoning of this one. Since foyaites and syenites are so often syngenetic, the proofs of sedimentary control for the one class of rocks are likely to affect belief in sedimentary control for the other class.

General Chemical Effects of the Absorption of Carbonate Rocks.—No experimental attempt has yet been made to show in detail the influence of the assimilation of limestone or dolomite on subalkaline magma. Obviously dolomite would not have the same influence on the syntectic or its differentiates as that exerted by pure calcium carbonate; this contrast offers one of the special problems not yet solved. Nevertheless, the scattered facts already known concerning this subject clearly favor the hypothesis here outlined.

Smelting operations agree with physico-chemical theory in showing that carbonate rock is a powerful flux for basaltic or other subalkaline magma. The effect must be specially great in plutonic chambers where the carbon dioxide is not allowed to escape as it is in the industrial melt. With increase of fluidity, any initial tendency to differ-

[1] F. D. Adams and A. E. Barlow, Geology of the Haliburton and Bancroft Areas, Memoir No. 6, Geol. Surv. Canada, 1910, pp. 227, 228, 332, and 408.

entiation must be strengthened. In general the magmatic stability itself is disturbed by the entrance of the new ions, so greatly contrasted in quality or quantity with those of the original solution. For two reasons, therefore, magmatic splitting is incited. As above noted, we have ready explanation for the usual failure of the unchanged syntectic phase, and of transitions to subalkaline types, to appear with the exposed alkaline rocks. The almost astonishing facility for differentiation in alkaline magma will be illustrated in a succeeding statement regarding several thin sills and laccoliths (page 437; see also page 237 ff).

The introduction of foreign calcium oxide into a basaltic magma has two chief effects. The new material inoculates the solution and causes an early separation of augitic or other lime-bearing molecules already potentially present. Because of its strong affinity for silica, the lime forms new molecules of more or less similar kinds. The gravitative settling of these units, either liquid or solid, must increase the alkalinity of the remaining solution.

If the new molecules are augitic—a common case—the foreign lime binds at least 2.5 times its own weight of silica. Other molecules would have the same desilicating effect on the original basalt. The eclectic theory predicts, therefore, that the feldspars of the substratum magma should be partly replaced by feldspathoids, nephelite, leucite, etc.

Since magnesia and iron oxide also enter, with the foreign lime, into the augite and other heavy molecules, the mother-liquor should be less ferromagnesian as well as less calcic than the original basalt. These are, in fact, the kinds of chemical contrasts existing between phonolite and basalt or between foyaite and gabbro. The desilication and allied processes are exemplified in xenoliths and external contact shells where pure carbonate rocks have so often been converted into amphibolites, garnet rocks, or other lime-silicate masses.

For lack of appropriate experimental work the exact influence of absorbed carbon dioxide cannot be stated. This compound, like the resurgent water, sulphur oxides, etc., cannot fail to affect the differentiation of the basaltic syntectic. Probably these magmatic gases are largely responsible for the upward transfer and local concentration of the alkalies. In what form the alkalies migrate, whether as carbonates, hydrates, aluminates, or silicates, is yet unknown; but the fact of their upward transfer on the large scale is proved by the formation of adinoles, by the feldspathization of roof rocks, and, it may be, by the existence of certain hot soda springs. The writer has been much impressed with the pneumatolytic habit of the many bodies of nephelitic and sodalitic rocks in the Hastings-Haliburton region, Ontario. These types often form the roof phases of the concordant, sill-like intrusions so characteristic of the district—a position expected on the gaseous-transfer hypothesis. (See pages 246 and 339.)

Giorgis and Gallo have described an experiment of present interest. They immersed three analyzed samples of Vesuvius lava in water and for two months kept a current of CO_2 passing through the mixture. At the end of that time it was found that the lavas had lost from 30 to 40 per cent. of their soda, the other constituents being but little altered in amount.[1]

In a volcanic vent occupied by molten basalt, which is actually absorbing limestone or dolomite, the chemical conditions must be very complex. Moderate concentration of the alkalies by gaseous transfer may affect a portion of the lava column which has also been somewhat desilicated, giving a melilite basalt, a nephelite basalt, a

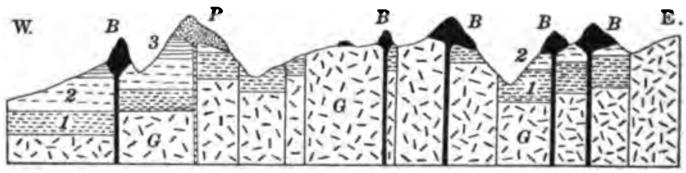

FIG. 193.—East-west section across le Livradois and le Comté, France. (After P. Glangeaud, Bull. serv. carte géol. France, No. 123, 1909, p. 17.) *G*, granitic basement; *1*, *2*, *3*, Oligocene; *B*, basalt and tephrite; *P*, phonolite.

basanite, or a nephelinite, which may be "fixed" by extrusion and thus, through chilling, be prevented from further differentiation. That splitting will normally occur in such a femic magma, if it has prolonged life, is suggested by the failure of melilite basalt to have a plutonic equivalent. Nephelite basalt and leucite basalt magmas, relatively abundant themselves, have extremely rare representatives among the granular rocks which have crystallized slowly in large subterranean chambers. Only with long life can the syntectic separate into the extreme submagmas. During most of its life the differentiation must be affected by: (a) the settling of cafemic constituents; (b) the rise of alkaline constituents; (c) the addition of new material from the wall rocks, which themselves are usually heterogeneous. Under such conditions we should expect the differentiates to be highly varied, both chemically and mineralogically. The variability of individual alkaline bodies and the great number of named alkaline species (out of all proportion to their volumetric importance) are both of the order expected on the syntectic hypothesis.

[1] G. Giorgis and G. Gallo, Gazetta, Vol. 36, 1906 (*i*), p. 137.

Further, the eclectic theory explains the preponderance of femic species among the extrusives of the alkaline clan, and the preponderance of salic species among its intrusives. During its initial, hot stage, even after some carbonate rock has been absorbed, the primary basaltic magma is eruptible with comparative readiness. As syntexis progresses, viscosity must increase and tend to prevent extrusion. Large-scale assimilation is possible only in large chambers. These

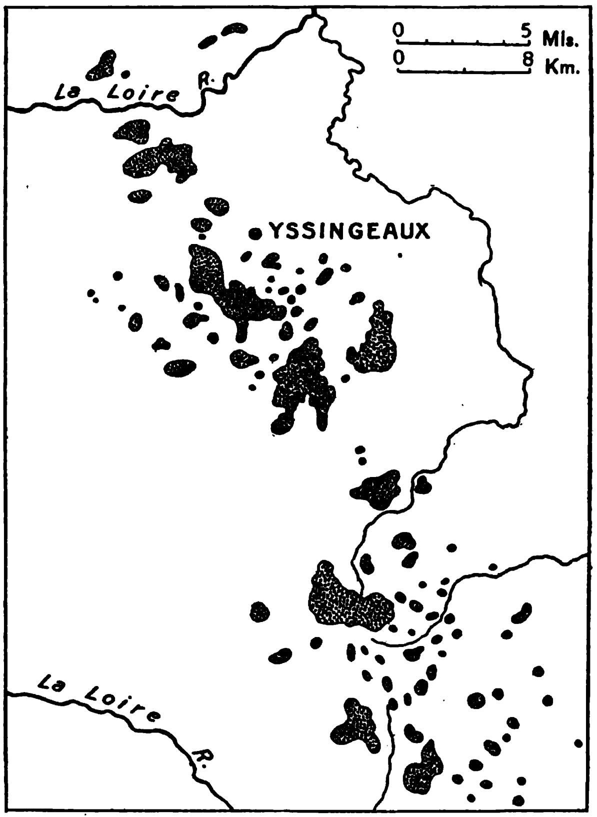

FIG. 194.—Map of phonolites (*dotted*) of the Velay. (After M. Boule, Bull. serv. carte géol. France, No. 28, 1892, p. 147.)

are generally capable of magmatic splitting after notable assimilation has ceased. The salic pole of the intrusive body, here as in the case of the other clans, will usually be the only one exposed in large quantity by rosion. The world's maps provide facts amply sufficient to show the parallel between the deductions and the actual distribution of igneous rocks. The nephelite basalts of Germany overwhelm the phonolites. The phonolites of France were erupted at many points but always in small volume (Figs. 193–4). In Italy leucite tephrites and basanites abound, while phonolitic lavas are rare. Among the intrusives, foyaite clearly dominates over the more femic nephelite syenites, over ijolites and their allies.

Evidence from the Mineralogy of Alkaline Rocks.—The offered explanation for most of the alkaline rocks involves a special mineralogy for them and one of its strongest merits is that it gives the key to a genetic problem which has hitherto had no adequate solution whatever.

(1) No reasonable doubt now remains as to the primary nature of the calcite enclosed in many eruptive bodies. A few granites contain it as a rare accessory but most of the calcite crystallized from igneous melts has been found in nephelite syenites and their close allies. Well-known examples are described in the memoirs on Alnö, Sweden; the Hastings-Haliburton area, Ontario; and the Ice River intrusive, British Columbia.

Cancrinite was discovered and first named at Miask (Urals), where, in company with scapolite and corundum, it occurs as a primary constituent of nephelite syenite in contact with thick limestone. According to Thugutt, its complex formula contains five molecules of $CaCO_3$, one molecule of Na_2CO_3, and, also suggestively, three molecules of sodium aluminate.[1] Preobrajensky reports that the nephelite syenite of upper Zarafshan (Turkestan) contains cancrinite, idiomorphic calcite, titanite, and sodalite. The cancrinite forms strips parallel to the contact with limestone which is intruded by the syenite.[2] Such facts inevitably suggest a syntectic origin for these minerals.

(2) Nephelite, leucite, sodalite, noselite (nosean), haüynite, analcite, corundum, spinel, and probably muscovite are characteristic constituents of alkaline rocks. Most of them do not occur in rocks which have been referred to the subalkaline clans. All are compounds such as might crystallize in subalkaline magma which has been desilicated in the manner described. The combined water of analcite and the hydroxyl molecule of muscovite are expected ingredients of a sedimentary syntectic. The liberation of alumina from silica and alkalies to form corundum and spinel is again a predictable result of the absorption of carbonates by subalkaline magmas. The recurrence of corundum in nephelite syenites, etc., cutting limestones, in Ontario, India, and elsewhere is not accidental. It is worthy of note that the Montana sapphires are found in minette dikes cutting thick limestone[3] (Fig. 119, p. 207). That these are due to "desilication" by the

[1] S. J. Thugutt, Neues Jahrb. für Miner. etc., 1911 (*i*), p. 45.

[2] P. Preobrajensky, Annals de l'Institut Polytechnique Pierre le Grand, St. Petersburg, Vol. 15, 1911, p. 293.

[3] W. H. Weed, 20th Ann. Rep., U. S. Geol. Survey, Pt. 3, 1900, p. 456.

intruded limestone, rather than to the crystallization of the alumina of accompanying shales, is suggested by the fact that the minettes of Montana, where cutting limestone, sometimes carry nephelite.[1] Moreover, Jensen has found a mineral with the properties of corundum in the melilite basalts of the Warrumbungle Mountains, New South Wales.[2] The oligoclase-corundum rock, plumasite, of California is another type, showing the tendency of alkaline types to carry free alumina. Its liberation finds general explanation on the carbonate-syntectic hypothesis.[3]

The picritic sill of Inchcolm island, Scotland, is bordered by a

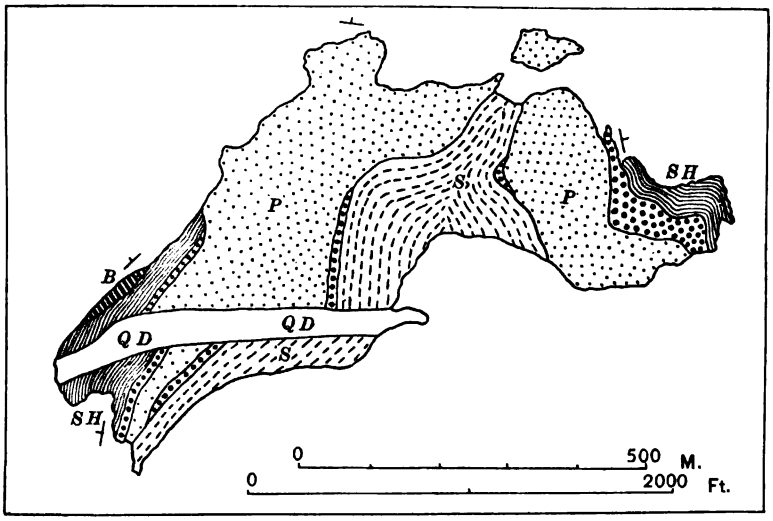

FIG. 195.—Map of Inchcolm Island, Scottish coast. (After R. Campbell and A. G. Stenhouse, Trans. Edin. Geol. Soc., Vol. 9, 1907, p. 121.) *S*, sandstones, etc., underlying sill; *SH*, shale, ash, etc., overlying sill; *B*, olivine-basalt lava; *coarse dots*, teschenite of sill; *P*, picrite of sill; *QD*, quartz-dolerite dike.

teschenitic phase, rich in primary analcite (Fig. 195). Campbell and Stenhouse are convinced that the magma has absorbed a considerable amount of the invaded calcareous sandstones and argillites.[4] They state that it is impossible to find a sharp limit between sediments and intrusive. Is this an actual case of desilication in place?

According to Lowe, the Lurcombe sill in Devonshire is vertically (gravitatively?) stratified, with a camptonitic phase at the roof,

[1] W. H. Weed, Little Belt Mountains Folio, U. S. Geol. Survey, 1899.
[2] H. I. Jensen, Proc. Linn. Soc., N. S. W., Vol. 32, 1907, p. 615.
[3] A. C. Lawson, Bull. Dept. Geol. Univ. California, Vol. 3, 1903, p. 219.
[4] R. Campbell and A. G. Stenhouse, Trans. Edinburgh Geol. Soc., Vol. 9, 1907, p. 133.

teschenite in the middle, and an augitic phase of the teschenite at the bottom. This intrusive body is enclosed in Culm sediments and has also evidently cut the underlying massive Devonian limestone.[1] The classic teschenite of Austria occurs in the same sill with picrite and a hornblende-free, diabasic type. The sill cuts the Teschen limestone and associated marly sediments. Here no decisive evidence has been found that the differentiation occurred in place.[2]

(3) The local excess of lime in "alkaline" magmas is indicated not only by primary calcite but by the common development of melilite, scapolite, wollastonite, lime-garnets, and perhaps anorthoclase itself. Though the solution of carbonate rock in basalt incites differentiation so that the salic sub-magma shall be poor in lime, it is obvious that, toward the close of the assimilating period, all of the foreign lime cannot be cleansed from the cooling, viscous, alkaline submagma. The hybrid rocks will thus vary greatly in composition, both according to the proportion of lime absorbed and according to the advance of differentiation registered in the submagma. The melilite basalts represent only moderate differentiation; they vary in alkaline content and some varieties approach the postulated cafemic pole of splitting in a basalt-limestone or basalt-dolomite syntectic. Becker has concluded that the melilite basalt of the Wartenberg, Germany, is an actual product of magmatic absorption of the invaded limestones.[3] Starabba reports that melilite was produced by the partial solution of limestone inclusions in the 1883, 1886, 1892, and 1910 lavas of Etna.[4] In these rocks and in the closely related melilite basalts, melilite is sometimes accompanied by wollastonite, haüynite, garnet, and perovskite, as well as by augite. Primary scapolite and calcite are associated in the nephelite syenites of the Hastings-Haliburton area of Ontario. The tinguaite of Spotted Fawn Creek, Yukon, contains essential leucite, with scapolite in its ground-mass.[5]

The lime-bearing minerals, titanite and perovskite, are also suspiciously abundant in many species of alkaline rocks. The more salic species, foyaite, phonolite, etc., generally tend to be correspondingly poor in ilmenite or titaniferous magnetite. Both facts are explicable on the view that these differentiates have been derived from a limestone-syntectic. Some ferrous iron should enter the augite and other cafemic molecules formed by inoculation with foreign lime. Titanic oxide is thus free to combine with lime, forming stable

[1] H. J. Lowe, Geol. Mag., Vol. 5, 1908, p. 344.
[2] V. Uhlig, Bau und Bild Oesterreichs, Vienna and Leipzig, 1903, p. 896.
[3] E. Becker, Zeit. d. deut. Geol. Gesell., Vol. 59, 1907, pp. 244 and 401.
[4] Stella Starabba, Rend. R. Accad., Lincei, Vol. 19, 1910, p. 755.
[5] C. W. Knight, Amer. Jour. Science, Vol. 21, 1906, p. 286.

compounds. These seem to be moderately "volatile" and, as in the Turkestan intrusives above noted, may be driven out into the surrounding limestone formation.[1] There are, in fact, field evidences that titanite tends to accompany the alkalies as they are magmatically concentrated. Associated in origin with the aegerite syenite of Bowral, New South Wales, are pegmatite veins charged with abundant titanite, ilmenite, and perovskite.[2] Benson notes that the alkaline (sodic) rocks of southern Australia and of eastern Australia are characteristically rich in titanic oxide.[3]

(4) The hypothesis predicts that free carbon should enter a syntectic if the absorbed limestone is carbonaceous. Graphite has, in fact, been described as among the magmatic products in the nephelite syenites of India and of Ontario.

The mineralogy of the alkaline rocks, though extensive, is highly specialized. At least sixteen species of minerals, either essential or accessory, are just those to be expected on the carbonate-syntectic hypothesis. Many of them, and particularly their actual *associations* in rocks, are most difficult of explanation on any other postulate. Synthetic experiments give full permission for belief in the preferred explanation. The reader will find a convenient summary of these experiments in the parts of Clarke's "Data of Geochemistry" dealing with analcite, cancrinite, corundum, garnet, graphite, haüynite, leucite, melilite, nephelite, scapolite, titanite, and wollastonite.[4]

It hardly needs emphasis that water as well as carbon dioxide must enter a limestone syntectic. The source of the water is either the carbonate rock itself or the usually associated shales or other silicious sediments. Resurgent water must co-operate in the segregation of alkaline submagmas and in the crystallization of minerals, like riebeckite, which form only in the presence of "mineralizers."[5] Like many syenites, soda-granites, albitites, oligoclasites, veins of potash feldspar, etc., are normally differentiated from syntectics of hydrous silicious sediments, rather than from carbonate syntectics. In general, the thesis that the segregation of alkalies in the alkaline rocks proper is largely caused by transfer in volatile solutions is greatly strengthened by the known facts concerning the aplites from subalkaline magmas.

Differentiation of Alkaline Rocks in Place.—The eclectic theory assumes the active control of gravity in magmatic splitting. This matter is so vital that it merits attention in the problem of each

[1] P. Preobrajensky, Annals de l'Institut Polytechnique Pierre le Grand, St. Petersburg. Vol. 15, 1911, p. 293.

[2] D. Mawson, Proc. Linn. Soc., N. S. Wales, Vol. 31, 1906, p. 579.

[3] W. N. Benson, Trans. Roy. Soc. South Australia, Vol. 33, 1909, p. 137.

[4] Bull. 491, U. S. Geol. Survey, 1911.

[5] G. M. Murgoci, Amer. Jour. Science, Vol. 20, 1905, p. 133.

igneous clan in turn. As with the gabbro, granite, granodiorite, diorite, and syenite clans, so here, the facts concerning sills and laccoliths are of the highest importance.

As noted in Chapter XII, the gravitative differentiation of the Shonkin Sag laccolith, the Square Butte laccolith, and the Lugar sill is obviously clear. In the first, nephelite syenite and shonkinite are polar differentiates of leucite basalt. In the second, sodalite syenite and shonkinite are similarly derived from leucite basalt. In the third, theralite and picrite are gravitative differentiates of "basaltic" teschenite magma.

Tyrrell has explained a picritic phase of the Benbeoch sill, West Scotland, as a gravitative differentiate of "kylite" after injection.[1] He notes that the Castle Craigs picrite-teschenite sill of Ayrshire shows magmatic splitting very similar to that at Lugar; and also details facts suggesting that, in the Howford Bridge sill of Ayrshire, analcite syenite is a gravitative differentiate of "essexite-dolerite."

The Prospect intrusion near Sydney, New South Wales, is a laccolithic sheet at least 300 feet thick, cutting Triassic shales and necessarily intruded through the underlying Paleozoic limestones and other sediments. The roof phase represents the magma as originally injected at this horizon; it is an essexite showing the phenomena of rapid chilling. It is underlain by a decidedly more salic, feldspathic essexite, succeeded below by an essexite layer with the maximum proportions of augite (38 per cent.) and ilmenite (16 per cent.). The floor of the sheet is not exposed. The splitting is not far advanced but it has been governed by the same general laws as those affecting the Montana and Scottish intrusives just mentioned.[2]

The Grosspriesen laccolith of the Bohemian Mittelgebirge exhibits sodalite syenite in outcrop. Hibsch's map shows that the cover of Tertiary sediments still largely remains. Hence this syenite phase occurs near the laccolithic roof, that is, in a situation suggestively like that of the sodalite syenite of Square Butte. The Grosspriesen syenite (sp. gr. 2.631) is closely associated with essexite (sp. gr. 2.855). Their genetic relation is not decipherable from the facts described.[3]

[1] G. W. Tyrrell, Geol. Mag., Vol. 9, 1912, pp. 73 and 123; Trans. Geol. Soc. Glasgow, Vol. 13, 1909, p. 309. This authority regards kylite as the plutonic equivalent of nephelite basalt.

[2] H. S. Jevons, H. I. Jensen, T. G. Taylor and C. A. Süssmilch, Proc. Roy. Soc. N. S. Wales, Vol. 45, 1911, p. 445, and Vol. 46, 1912, p. 111. Taylor and Jevons discuss (page 459) the possibility of overhead stoping in this essexite. Their estimates of rock densities show that underhand stoping would be the only kind possible in this case. Obviously such a thin sheet could not be expected to illustrate stoping except on a most insignificant scale.

[3] J. E. Hibsch, Tschermak's Min. u. Pet. Mitt., Vol. 21, 1902, pp. 157 and 465.

The Borolan laccolith at Cnoc-na-Sroine, Scotland, measures 4 miles by 2.5 miles in outcrop, with a probable original thickness of about 0.25 mile. The roof has been eroded away. Shand's section is reproduced in Fig. 196. The intrusion is stratified in the following order:

		Approx. spec. gravity
	Erosion surface	
Phase 1....	Quartz syenites...........................	2.625–2.635
Phase 2....	Transition zone of quartz-free syenite.......	2.65
Phase 3....	Melanite-nephelite syenite and ledmorite...	2.74 –2.78
	Base concealed	

Shand favors the hypothesis that the concealed floor phase is composed of melanite pyroxenite, like that observed as locally intrusive into Phase 3.[1]

The advanced character of this clearly gravitative splitting, in a sheet of rather moderate thickness, is one more illustration of the

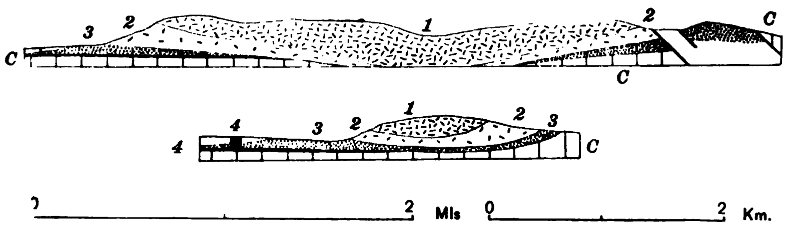

FIG. 196.—Sections of Cnoc-na-Sroine laccolith, Scotland. (After S. J. Shand, Trans. Edin. Geol. Soc., Vol. 9, 1910, p. 379.) *C*, Cambrian; *1*, quartz syenites; *2*, transition rocks; *3*, melanite-nephelite syenites, augite-nephelite syenites, etc.; *4*, hypothetical ultra-basic layer. Upper section is N.W.–S.E.; lower section is S.W.–N.E.

decided fluidity of alkaline magmas, however viscous many artificial melts may be. This case throws light on the syngenesis of soda-granites, nordmarkites, foyaites, etc. It throws suggestive light on the problems of origin in connection with the much greater rock assemblages in the Christiania Region and at Predazzo, etc.

The very able memoir by Ussing, on the Julianehaab district of Greenland, describes a remarkable group of alkaline rocks which have crystallized from magmas differentiated, at least in part, under the dominating influence of gravity.[2] The sodalite foyaite, "naujaite," lujavrite, and "kakortokite" of the Ilimausak intrusion—all related

[1] S. J. Shand, Trans. Edinburgh Geol. Soc., Vol. 9, 1910, p. 376.

[2] N. V. Ussing, Geology of the Country around Julianehaab, Greenland, Copenhagen, 1911, pp. 318, 348, etc.

to foyaite—are so interpreted by Ussing (Fig. 197–8). These and the other rocks of the mass occur as successive, nearly horizontal sheets, named in order, from above downward:

	Thickness (meters)	Spec. gravity
Arfvedsonite granite	150–400	2.66–2.72
Quartz syenite	0–20	(?)
Pulaskite	10–30	2.72
Foyaite	0–10 (?)	2.67
Sodalite foyaite	2–150 (average, 100 m.)	2.65
Naujaite	200–600 (average, 300 m.)	2.53
Lujavrites and kakortokites	600+	2.75–3.12

The naujaitic layer (highly sodalitic) is explained by an upward transfer of the sodalite molecule from the deeper part of the mass.

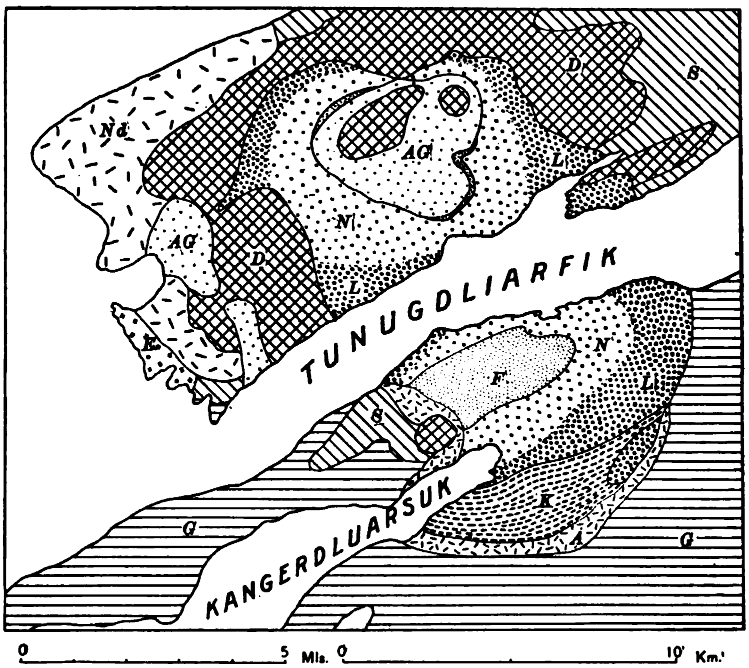

FIG. 197.—Map of the Ilimausak intrusion, Greenland. (After N. V. Ussing, Medd. om Grönland, Vol. 38, 1911, Pl. 3.) *G*, granite; *S*, sandstone; *D*, diabase and porphyries; *E*, essexite; *A*, augite syenite; *L*, lujavrite; *K*, kakortokite; *N*, naujaite; *F*, sodalite foyaite; *Nd*, nordmarkite; *AG*, arfvedsonite granite.

The more ferrous and less aluminous lujavrite-kakortokite magma is explained as the residual liquor left after the gravitative removal of the sodalite. Ussing considered it likely that this substance was transferred in the form of solid crystals. For present purposes it is not necessary to decide between that hypothesis and the alternative one of liquation. The sodalite foyaite above the naujaite represents nearly the chemical composition of the magma before this differentiation took place. Ussing did not attribute the foyaitic phase to the relatively quick chilling of the original magma near the roof of the intrusion but gave a hypothetical explanation detailed on page 354 of his memoir. That hypothesis, involving the rise of magmatic gases, also implies gravitative control.

Ussing explained the arfvedsonite granite phasė as probably due to the assimilation of the sandstone intruded by the foyaitic magma. It is shown that the clearly stoped-down blocks of sandstone are surrounded with thick shells of this granite merging outwardly into alkaline, subsilicic syenite. The syenite in its turn merges into the nephelite-bearing rocks. If this view is correct, the assimilation must have

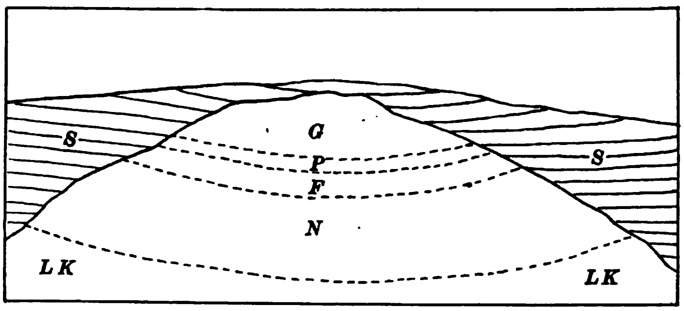

FIG. 198.—Schematic section of the Ilimausak intrusion. (Same ref. as for Fig. 197, p. 322.) *S*, sandstone, diabase, etc.; *LK*, lujavrite and kakortokite; *N*, naujaite; *F*, sodalite foyaite; *P*, pulaskite; *G*, arfvedsonite granite.

partly occurred in place. In this connection the discovery of a layer of augite syenite at the *lower* contact and below the denser lujavrites of the neighboring Igaliko intrusion is significant.[1] Nevertheless it is possible that the granitic magma was largely differentiated from the sandstone syntectic and solidified *before* the main foyaitic magma was differentiated. The granitic magma was clearly less dense than the undifferentiated foyaite, so that this initial splitting was controlled by gravity. Afterward the deeper-lying, still fluid foyaite split into the strongly contrasted naujaite and lujavrite sub-magmas. This differentiation affords a noteworthy illustration of the upward transfer of alkali, the overlying naujaite being extremely rich in sodalite. Allan has observed a similar segregation of sodalitic rock near the roof of the alkaline intrusion at Ice River, British Columbia.[2] (See also p. 235.)

[1] See sections in Ussing's memoir on pp. 252, 253, and also those on pp. 38, 39, 42, and 61.

[2] J. A. Allan, Geology of the Ice River District, a thesis abstract published by the Massachusetts Institute of Technology, 1912, p. 11.

The problem is much too delicate for dogmatism but one cannot but agree with Ussing that the Ilimausak intrusion, complicated as it is, does illustrate gravitative differentiation on a large scale, as shown in the relation of the highly sodalitic layer to its more ferric associate.

In passing, it may be noted that the Ilimausak and still larger Igaliko "batholiths" often have concordant or roughly concordant relations to the invaded sandstone. The contacts of the Ilimausak intrusion are like those at the roof of a chonolith or an irregular, partly cross-cutting laccolith. The sections on pages 252 and 253 of Ussing's book, when compared with the map in Plate IV, strongly suggest that the Igaliko body is an irregular laccolith with its base exposed.

The memoir further describes an unusually perfect and full illustration of primary banding. The kakortokites of the lowest visible phase are arranged in layers of black, white, and red colors, corre-

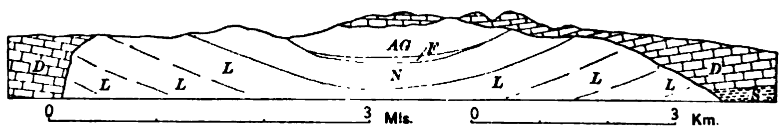

Fig. 199.—Actual section of the Ilimausak intrusion from W. S. W. to E. N. E. (Same ref. as for Fig. 197, Pl. 6.) S, sandstone; *D*, diabase and porphyry (sheets); *L*, banded lujavrite, with lenses and fragments of naujaite; *N*, naujaite; *F*, sodalite foyaite; *AG*, arfvedsonite granite.

sponding to great differences in specific gravity and mineral composition (Fig. 199).

"The peculiar kind of stratification characterizing the kakortokitic complex will appear from the following list of a number of consecutive sheets:

	Thickness	Specific gravity
Black kakortokite	ca. 2–3 meters	ca. 3.12
White kakortokite	ca. 6–9 meters	ca. 2.76
Red kakortokite	ca. 1–2 meters	ca. 2.85
Black kakortokite	ca. 2–3 meters	ca. 3.12
White kakortokite	ca. 6–9 meters	ca. 2.76
Red kakortokite	ca. 1–2 meters	ca. 2.85
Black kakortokite	ca. 2–3 meters	ca. 3.12

"The succession as given in this table continues through a total thickness of about 400 meters, the number of individual sheets amounting to more than a hundred, while the number of repetitions of color sets is about forty. It is worth mentioning that the red sheets in many places are badly developed or even wanting, but even in such cases the lowermost portions of the white sheets or the uppermost portions of the black ones are relatively rich in eudialyte. . . . . .

"That gravitative separation is able to account for the differentiation will appear from the following consideration. The black kakortokite sheets (sp. gr. 3.12) are characterized by the abundance of arfvedsonite (sp. gr. 3.4); the red sheets (2.85) which overlie the black ones abound in eudialyte (2.9); and the white rock (2.76) which covers the red sheets has alkali felspar as its dominant mineral (2.6). The arrangement thus agrees with what should be expected if it were due to gravitation. . . . . .

"For the banded kakortokite of the Ilimausak complex the simplest supposition is perhaps that the recurrent layers have originated in consequence of repeated variations in pressure. Each reduction in the pressure may have caused the dissociation of a certain quantity of volatile matter from the magma, and this process in its turn may have caused the crystallization of a certain quantity of the magma."[1]

The variation of pressure is supposed to be due to volcanic outbursts from the magma chamber. The present writer may also suggest the inquiry as to whether a principle which has been experimentally illustrated may apply to this and many other cases of banding in igneous rocks. If silver nitrate is allowed to diffuse into a gelatin film containing potassium dichromate, there ensues an intermittent precipitation of silver dichromate, shown by alternating bands of color.[2] Is it possible that, under certain conditions, liquation is intermittently, rhythmically produced in magmas?

Similar primary banding is seen in the great foyaitic laccolith of the Kola peninsula, in the malignite-nephelite syenite body of Kruger mountain in the Cascade range (Canada-United States boundary line), and in many other plutonic alkaline masses. Multiplied examples show the importance of active attack on the problem of explaining these differentiations in place.

Chemical Contrast of Alkaline Volcanic Species and the Corresponding Plutonic Species.—As in all the other clans so far described, gravitative control should be manifested in the chemical relation between each alkaline volcanic type and its equivalent plutonic type. For this comparison averages of composition are obviously more significant than single analyses. Table II shows the situation for the more important pairs of averages. See Columns 35, 36, 75, 76, 80, 81, 88, and 89. The comparisons show, in every case, the more salic nature of the extrusive phase, doubtless corresponding to lower density for its magma.

Eruptive Sequence in Alkaline Provinces.—The demonstrated ease with which alkaline magmas differentiate in the many sheets and lac-

[1] Geology of the Country around Julianehaab, Greenland, Meddelelser om Grönland, Vol. 38, 1911, pp. 356, 358, 360.

[2] Cf. R. E. Liesegang, Zeit. phys. Chemie, Vol. 59, 1907, p. 444.

coliths described leads to the deduction that the order of eruption in alkaline provinces will be somewhat variable. Yet, according to the eclectic theory, the sequence for the larger intrusive masses should generally be from femic to salic. Such, in fact, is the eruptive order already determined for many provinces, *e.g.*, the Okanagan composite batholith; Midway district, British Columbia; Red Hill, New Hampshire; Predazzo, Tyrol; Christiania Region; Julianehaab, Greenland; Kola peninsula, etc. A typical illustration is found in the "stock" in the Oberwiesenthal, Erzgebirge. It is chiefly composed of nephelite basalt locally transitional, through sanidine phonolites and leucite phonolites, into true phonolite, and cut by numerous dikes and small "stocks" of phonolite. Sauer concluded that the basalt was not yet cold when the phonolite was erupted.[1]

The eclectic theory further implies that the eruptives from volcanoes of the central type should often alternate from femic to salic and conversely. The reason for this deduction is the same as that given on page 372 for the analogous relation of trachytes, dacites, etc. to basalt. Several illustrations are given in the table of Appendix B, especially the sequence for: Mont Dore, le Velay and le Mézenc, Cantal, Limagne, France; Rhine provinces, Germany; Bohemia; Lipari (Eolian) Islands; New South Wales and Victoria, Australia.

In general, the ferromagnesian or cafemic differentiate of a limestone syntectic must be in depth too great for ready eruption. This deduction from the theory partly explains the cause of the relative rarity and small individual volume of the visible shonkinitic, ijolitic, bekinkinitic, limburgitic, and augititic eruptives. Unless these rocks are differentiates in place, they should, as a rule, be erupted after the corresponding overlying salic submagmas have solidified. According to Shand, this has actually occurred at Loch Borolan, where the nephelitic syenites are distinctly cut by the syngenetic melanite pyroxenite. (See page 439.) Similarly the jacupirangitic type, yamaskite, forms dikes cutting the essexite of Yamaska Mountain, Quebec. Other dikes of salic nephelite syenite, also cutting the essexite, have the appearance of being complementary to the yamaskite.[2]

Complementary Dikes of the Alkaline Clans.—Diaschistic dikes have had a disproportionate share of attention in many discussions on magmatic differentiation. As a rule they are peculiar in chemical composition and their magmas are not represented in stock, batholith, great laccolith or lava flood. The so-called complementary dikes are the relatively minute products of magmatic splitting which has doubt-

[1] R. Lepsius, Geologie von Deutschland, Part 2, 1903, p. 61; A. Sauer, Erläut., Sektion Kupferberg, 1882, and Sektion Wiesenthal, 1884 (Geol. Survey of Saxony).

[2] G. A. Young, Ann. Rep. Geol. Surv. Canada, Vol. 16, Part H, 1906, p. 36.

less taken place according to methods different from those responsible for the larger rock-bodies. The complementary dikes of the alkaline clans, as of all the others, seem to find best explanation in two different principles: gaseous transfer, and the "squeezing-out of residual magma" in the freezing stage of an abyssal wedge or of its satellite.

CHAPTER XXI

PERIDOTITE CLAN AND MAGMATIC ORES

Included Species

Most of the "ultra-basic," femic species of igneous rocks may, for present purposes, be grouped in a "peridotite clan." It will include the eruptive pyroxenites as well as peridotites proper. Many large bodies of iron, chromium, copper, nickel, and sulphur ores are magmatic in origin and syngenetic with members of the peridotite clan. Such ores will be briefly discussed in the present chapter, though a host of details must be left to the standard works on ore deposits.

The peridotite clan includes the rock species named as follows:

Plutonic Types

Essential Component	Species
Olivine.	Dunite.
Olivine + rhombic pyroxene.	Harzburgite (saxonite).
Olivine + diallage.	Wehrlite.
Olivine + diallage + rhombic pyroxene.	Lherzolite.
Olivine + amphibole.	Amphibole peridotite; *var.* scyelite.
Olivine + amphibole + pyroxene.	Cortlandite.
Olivine + biotite.	Mica peridotite, *var.* kimberlite.
Pyroxene (+ amphibole).	Pyroxenite; *vars.* websterite, bronzitite, hypersthenite, diallagite, kosvite.
Hornblende.	Hornblendite.

Effusive Types

Picrite.
Picrite porphyrite.

General Statement of Origin

The eclectic theory implies that these rocks are extreme differentiates of the primary basaltic magma or of basaltic syntectics.

The facts of the field can only be explained by recognizing two distinct modes of differentiation. In the one case, the unit of differentiation is a small, "dry" mass (either liquid or solid) of the ultra-femic silicate; in the other case, the unit of differentiation is a solution of such silicate in volatile matter which acts as a transferring agent. Segregation of the units of the first type has clearly been responsible for the larger bulk of the rock species listed. It is a process inevitably expected on the eclectic theory, whether the primary basalt spontaneously differentiates or whether it splits after the solution of foreign rock. Most of the material actually present in a peridotite should, however, originate in the primary basalt.

Relation to the Gabbro Clan.—Rosenbusch and others have forcibly indicated the close genetic connection of many dunites, wehrlites,

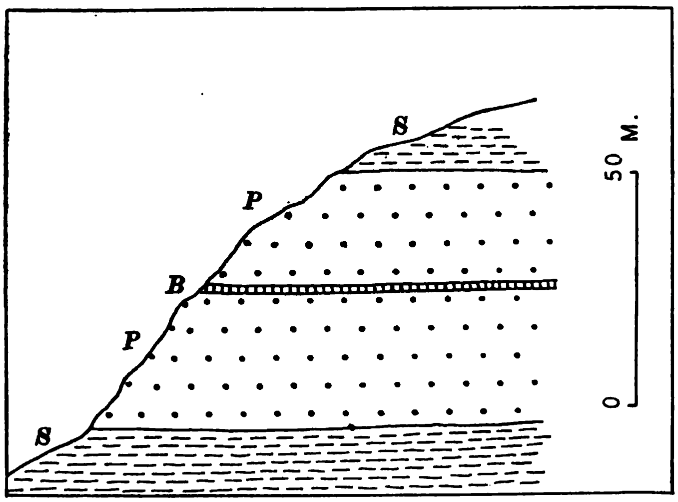

FIG. 200.—Section of composite sill in Greenland. (After A. Heim, Medd. om Grönland, Vol. 47, 1911, p. 203.) *S*, Cretaceous sandstone; *P*, peridotite sill; *B*, basalt sill. Illustrating close association between basalt and peridotite.

amphibole peridotites, hornblendites, lherzolites, pyroxenites, and picrites with basalt, gabbro, or diabase (Fig. 200 and 201). Wehrlite is a "feldspar-free olivine gabbro." Harzburgite is a "feldspar-free olivine norite," and is intimately associated with norite in the Harzburg region itself. All or nearly all these types are locally charged with basic plagioclase and thus show actual transition into gabbro, norite, or diabase.

The gravitative differentiation of anorthosite, as described in Chapters XII and XV, implies the segregation, in depth, of the monomineralic dunite magma, the bimineralic wehrlite or harzburgitic magmas, or the trimineralic lherzolitic magma. The correctness of this view is supported by several principal facts additional to those mentioned in the last paragraph.

1. Obvious differentiation in place has caused the dunitic, hypersthenitic, wehrlitic, and lherzolitic nodules, schliers, or layers in basalts, pyroxene andesites, gabbros, and anorthosites.

2. In recent years a number of cases have been recorded, showing the gravitative assemblage of such units. Some of these may here be recalled. Dunite, diallagite, and other pyroxenites, are found at the floor of the Duluth laccolith.[1] Pyroxenite and femic norite occur at the northern contact (probably the floor) of the Chibougamau anorthositic intrusion. (See page 326.) Hornblendite and pyroxenite are developed in the Glamorgan gabbro along its northern contact, which appears to be its floor. (See page 327.) Pyroxenites and ultrafemic norites are floor phases of the Bushveldt laccolith, Transvaal, and of the Preston gabbro laccolith, Connecticut. (See pages 350 and 353.) Toward the bottom of the thick Insizwa sheet of East Griqualand, the olivine gabbro and norite become increasingly femic and at last peridotitic.[2] Wehrlite and olivine-rock (serpentine) seem to be floor differentiates in at least one intrusive sheet of the Sinni valley,[3] Italy (Fig. 202). These Italian peridotitic rocks are overlain by norite and gabbro passing into plagioclasite at the top of the intrusive.[3] Duparc and Wyssotzky emphasize the density stratification so wonderfully repeated in *seven different areas* of peridotites in the Ural mountains. In each district dunite passes upward into pyroxenites, which in turn are overlain by gabbroid types of increasing acidity.[4]

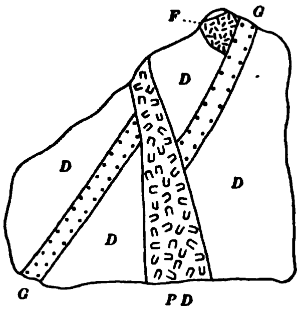

FIG. 201.—Plan of a rock-group in Scotland. (After J. W. Judd, Quart. Jour. Geol. Soc., Vol. 41, 1885, p. 359.) *D*, dunite; *F*, plagioclase segregation in the dunite; *G*, gabbro vein cutting the dunite; *PD*, porphyritic dunite cutting the gabbro. Illustrating the close association of gabbro, dunite, and feldspar rock.

Other floored injections illustrate gravitative differentiation on the way to producing species that belong to the peridotite clan. Iddings

[1] W. S. Bayley, Jour. Geol., Vol. 2, 1894, p. 814; Vol. 3, 1895, p. 1.

[2] A. L. du Toit, 15th Ann. Rept. Geol. Comm., Cape of Good Hope, 1910, p. 111.

[3] C. Viola, Boll. R. Com. geol. d'Italia, 1892, p. 105. Cf. Rosenbusch's Mikroskopische Physiographie der Massigen Gesteine, 4te Aufl., 1907, p. 342.

[4] L. Duparc, Archives des Sciences Phys. et Nat., Vol. 31, 1911 (Geneva); N. Wyssotzky, Mém. Comité Géol. de la Russie, Nouv. sér., livr. 62, 1913.

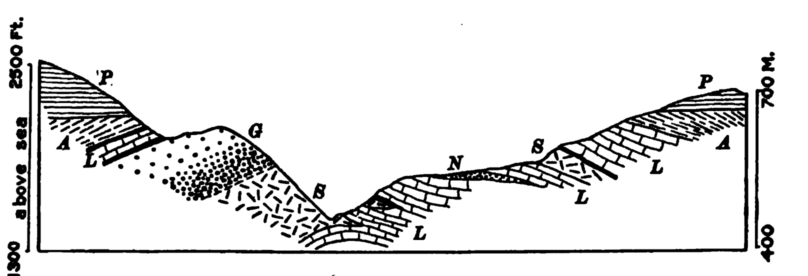

FIG. 202.—Section of Sinni Valley, Italy. (After C. Viola, Boll. R. Com. geol. d'Italia, Vol. 23, 1892, p. 105.) *L*, Eocene limestone; *A*, Eocene argillite; *S*, peridotite (serpentinized); *G*, gabbro passing above into plagioclasite; *N*, norite; *solid black*, granite and aplite; *P*, Pliocene conglomerate, etc. Horizontal scale, 1:30,000.

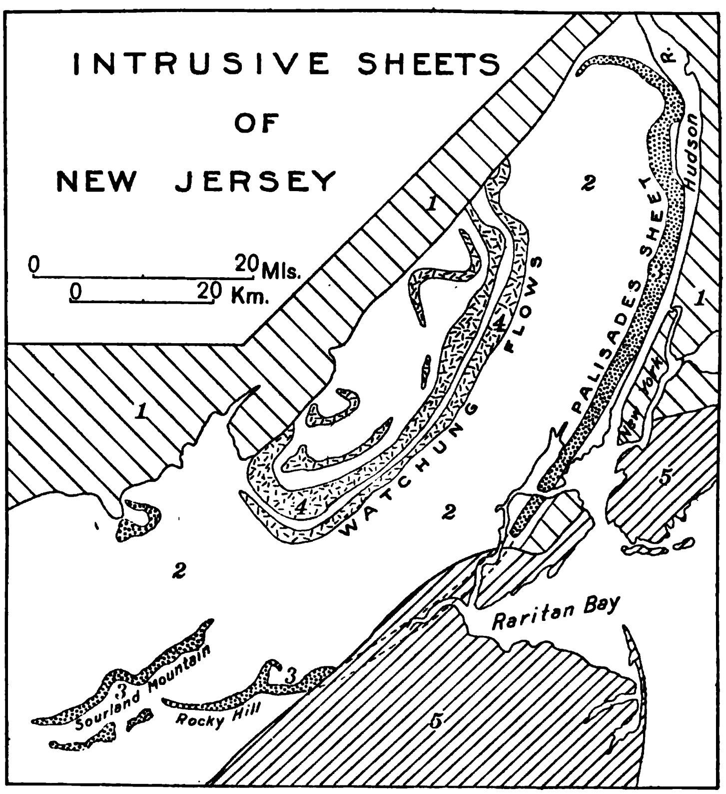

FIG. 203.—Map of the Palisades sheet, New Jersey. *1*, crystalline rocks; *2*, Triassic sediments; *3*, intrusive diabase (Triassic); *4*, extrusive basalt (Triassic); *5*, Cretaceous and later sediments.

found a decided enrichment of augitic material at the bottom of an intrusive sheet at Electric Peak, Yellowstone National Park.[1] A phase of the Palisades (New Jersey) diabase specially rich in olivine has been described by Lewis as due to settling of the olivine substance in this great intrusive sheet (Fig. 203).[2] Some of the floor phases in the Purcell sills of British Columbia (page 344) approach hornblendite in composition.

3. The argument for the spontaneous derivation of pyroxene andesite and pyroxene porphyrite from primary basalt (page 375) is in manifest relation to the problem of the peridotites. That explanation is amply supported by the close field association of the andesites with various peridotites as well as with undifferentiated basalt. Instances of such association[3] are so abundant that it is unnecessary to go into details in this book.

In the nature of the case volcanic pipes can but rarely demonstrate the advanced spontaneous splitting of basalt under the control of gravity. Yet the simultaneous eruption of augite andesite and an ultrafemic basalt at the active vent of Réunion has much value in illustration of the general process. (See page 228.)

Ultra-ferromagnesian and Ultra-cafemic Differentiates of Syntectics.—The eclectic theory holds that many rock bodies belonging to the peridotite clan are gravitative differentiates of syntectics. The precipitation of magmatic units rich in iron, magnesium, and lime is to be expected, partly because of the mere fluxing of basalt by basic sediments, partly because of inoculation with and supersaturation by the foreign lime and other substances. The character of the precipitate should vary with that of the absorbed material. It is, therefore, important to observe that the ultra-basic differentiates of the alkaline magmas are those appropriate to the limestone-syntectic hypothesis.

Rosenbusch has pointed out the syngenesis of pyroxenites with members of the gabbro-diorite series and with members of the alkaline series, such as essexites, monzonites, shonkinites, and theralites. The "alkaline" pyroxenites are exactly the rock types which should be most readily formed in the depths of a syntectic of carbonate rock with basalt or with one of its many differentiates. Other members of the peridotite clan should be far less commonly developed in the syntectic, and such is the fact.[4] Rosenbusch gives examples of the differentiation

[1] J. P. Iddings, Monograph 32, Part 2, U. S. Geol. Survey, 1899, p. 82.

[2] J. V. Lewis, Ann. Rep. State Geologist of New Jersey, 1907, p. 131.

[3] Compare Memoir No. 38, Geol. Surv., Canada, 1912, p. 782.

[4] See H. Rosenbusch, Mikroskopische Physiographie der Massigen Gesteine, 4te Aufl., 1907, p. 452.

of pyroxenite from alkaline magmas. Here we need note only a few of the more or less celebrated associations. This cafemic type appears with: the Duppau theralite of Bohemia; the Monteregian essexite of Quebec; the Gran essexite of Norway; the monzonite of Monzoni, and the syenites of Predazzo, Tyrol; the phonolites, etc., of the Sundance quadrangle, Wyoming-South Dakota; the phonolites of Southern Abyssinia; the tephrite etc. of the Cape Verde Islands; and the nephelite syenites of Ontario.

The relation of melanite pyroxenite to the syenites of the Loch Borolan laccolith is a striking case in point. Shand suggests that their derivation has taken place within the laccolithic chamber itself. (See page 439 and Fig. 196.)

Olivine-rock segregations in place are fairly common in trachydolerites and have been found in the leucite basalt of the Gaussberg, Antarctica,[1] and in the famous nephelite syenite of Alnö.[2] True peridotite (picrite) and olivine gabbro accompany the nephelite syenites of the Port Coldwell region, Ontario, but it is not known whether the peridotite is a differentiate of the alkaline magma rather than of the subalkaline.[3] The syngenesis is more evident in the intrusive sheets carrying both "picrite" and teschenite, near Teschen, Austria; at Inchcolm Island, Lugar, Barnton, Ardrossan, Lethan Hill, and other localities in Scotland.[4] True (effusive) picrites accompany the many alkaline species at the La Palma "caldera" of the Canary Islands, but feldspar basalts also compose part of this volcano and again doubt must exist as to the immediate affinities of the picrites.[5] Exactly the same problem faces the petrogenist dealing with the great igneous suites in Tahiti and Réunion.[6] The delicacy of his decision illustrates again and again the exceeding closeness of the genetic bond between the subalkaline and alkaline rocks. Any general theory must recognize the fact emphasized by Rosenbusch, that the true picrites are generally derivatives of diabasic or basaltic magma. Why, then, are they so often found in many typical alkaline provinces? For the eclectic theory this question carries no mystery.

As noted in the fourth edition of Rosenbusch's hand-book (p. 457), Carvill Lewis and Lacroix have remarked the "alkaline" affinities of South African kimberlite, which, according to Rogers, is linked geo-

[1] R. Reinisch, Deutsche Südpolar Expedition, 1901–1903, Berlin, 1906, Bd. 2, Heft 1, p. 75.

[2] A. G. Högbom, Geol. Fören. Stockholm Förhand., Vol. 31, 1909, p. 356.

[3] H. L. Kerr, 19th Ann. Rept. Bur. Mines Ontario, Vol. 19, Pt. 1, 1910.

[4] See pages 243 and 435; and G. W. Tyrrell, Trans. Geol. Soc. Glasgow, Vol. 13, Pt. 3, 1909, p. 298.

[5] C. Gagel, Zeit. Ges. für Erdkunde, Berlin, 1908, pp. 168 and 222.

[6] A. Lacroix, Comptes Rendus, Vol. 151, 1910, p. 121; Vol. 155, 1912, p. 538.

logically with the abundant melilite basalt filling many volcanic vents in the region.[1]

Most wehrlites are differentiates of gabbroid magma; but some are more or less certainly derivatives of alkaline magmas. Rosenbusch notes a wehrlitic dike associated with the alkaline types of Monzoni. The present writer has found wehrlitic segregations in the Hawaiian trachydolerite; Boulton finds them in the monchiquite of Golden Hill, Monmouthshire, England.[2]

Hornblendite is a large-scale differentiate in the Glamorgan gabbro intrusion of Ontario and may have been segregated by gravity. (See page 327.) The anorthosite of Chibougamau, Quebec, is accompanied by dikes and sills of hornblendite, pyroxenite, and dunite, in such relations that they appear to represent types actually complementary to the feldspar rock.[3] The hornblendite of the Sierra Nevada, California, is transitional into olivine gabbro.[4]

On the other hand, hornblendite forms segregations in alkaline magmas; for example, in the Norrbotten syenite of Sweden.[5] It is one of the femic differentiates of the essexitic magma at Gran, Norway.[6]

Reviewing the ground this rapidly traversed, we observe that expectation of gravitative control in the differentiation of peridotites is fully met by the facts concerning sills and laccoliths, which again must eclipse all other types of igneous bodies in giving required information. The principle of gravitative control explains: (a) the comparative rarity of peridotitic intrusions, for the eruption of an abyssal phase is manifestly less readily accomplished than that of the salic, overlying phase; (b) the relatively small size of every mass belonging to the peridotite clan; (c) the prevalence of the dike form of intrusion for peridotites and pyroxenites; (d) the general absence of vesicular structure in the picrites, since the volatile substances in a differentiated magma rise away from the ultra-femic phase.

Species Formed by Gaseous Transfer.—Some of the hornblendites seem to have been emplaced under conditions analogous to those of ordinary pegmatites. The meta-diorite of the Mother Lode district, California, passes peripherally into very coarse-grained hornblendite carrying accessory epidote, muscovite, and quartz.[7] Both the grain of the mass and the character of its accessory minerals suggest this

[1] A. W. Rogers, Geology of Cape Colony, London, 1905, p. 346.

[2] W. S. Boulton, Quart. Jour. Geol. Soc., Vol. 67, 1911, p. 460.

[3] A. E. Barlow, J. C. Gwillim, and E. R. Faribault, Report on the Chibougamau Region, Quebec, 1911, p. 164.

[4] Jackson Folio, U. S. Geol. Survey, 1894, p. 4.

[5] P. Geijer, Geol. För. Stockholm Förhand., Vol. 34, 1912, p. 183.

[6] W. C. Brögger, Quart. Jour. Geol. Soc., Vol. 50, 1894, p. 15.

[7] Mother Lode District Folio, U. S. Geol. Survey, 1900, p. 4.

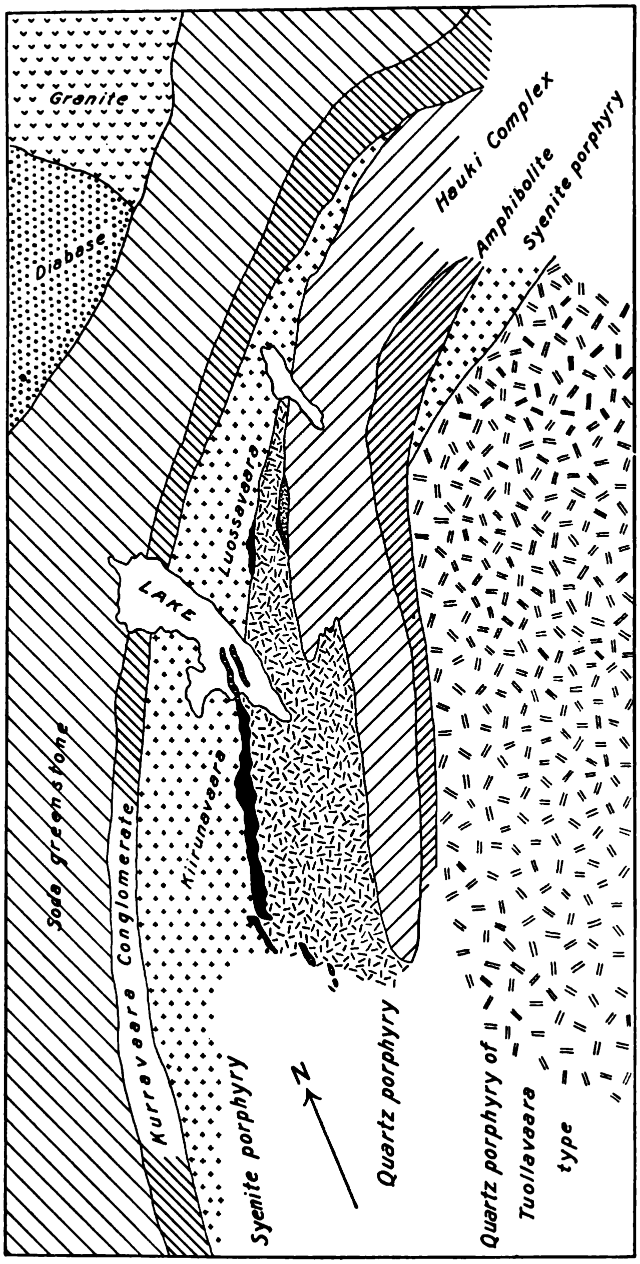

FIG. 204.—Map of the Kiruna district. (After Lundbohm and Geijer.) Scale, 1:120,000.

analogy. It may be recalled that the experimental formation of amphibole has never succeeded if water is absent from the melt. The writer has often observed masses or lenses of hornblendite segregated in the shear zones of dynamically metamorphosed granodiorites and gabbros, in the British Columbia mountains. Clapp has recently given a similar explanation of the hornblendite found in the Sooke gabbro of Vancouver Island.[1]

There can be little doubt that these segregations are due to gaseous or vapor transfer, and that such cases tend to corroborate the view that water-gas and other volatile substances have co-operated in the formation of certain hornblende rocks which have been more directly derived from magmas. In this connection one may recall Heim's clear illustration of gaseous transfer as responsible for the amphibole (kaersutite) segregations at Karsuarsuk, Greenland. (See page 402.)

Magmatic Ores.—Many small masses of titaniferous iron ores are obviously local differentiates of gabbroid magma or of its own deriva-

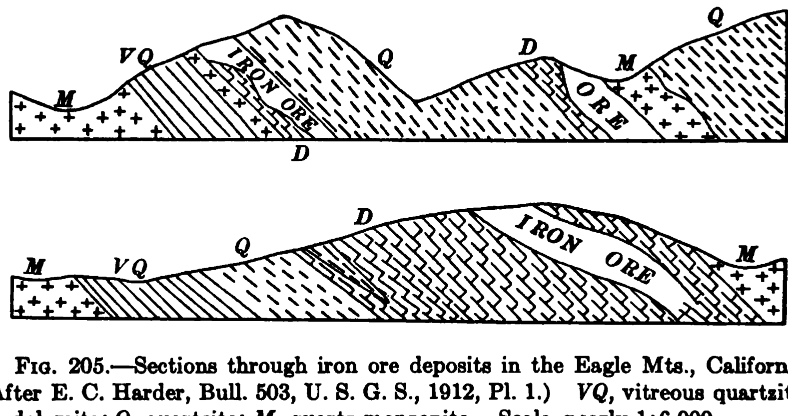

FIG. 205.—Sections through iron ore deposits in the Eagle Mts., California. (After E. C. Harder, Bull. 503, U. S. G. S., 1912, Pl. 1.) *VQ*, vitreous quartzite; *D*, dolomite; *Q*, quartzite; *M*, quartz monzonite. Scale, nearly 1:6,000.

tives, anorthosite, etc. In his admirable statement for the Adirondack ores, Kemp expresses the view that the differentiated oxides, like the silicate sub-magmas, separated while still in the liquid state.[2] Vogt, another specialist on this problem, agrees with Kemp.[3]

That gravity has often controlled the segregation of the larger bodies of magmatic iron ore is already clear. These form significant floor phases of the Bushveldt and Duluth laccoliths. Other masses have unilateral distribution in the great (probably laccolithic) injections of the Bergen district; of Glamorgan township, Ontario; and of the

[1] C. H. Clapp, Memoir No. 13, Geol. Surv. Canada, 1912, p. 123.
[2] J. F. Kemp, 19th Ann. Rep., U. S. Geol. Survey, Pt. 3, 1899, p. 417.
[3] J. H. L. Vogt, Norsk Geol. Tidsskrift, Bd. 1, No. 2, 1905, p. 6.

Chibougamau district, Quebec. (See pages 326 and 332.) The justice of the conclusion reached by Coleman and Barlow, that the sulphide ores of Sudbury are magmatic differentiates segregated by gravity, is shown not only by the plain facts of the local field but by the recent discovery of a perfect parallel in the Insizwa sheet of East Griqualand. (See page 349.) Ores of copper and of chromite also occur along the lower contact of the Bushveldt laccolith.[1]

The relation of the very large iron-ore deposits of Kiruna, Sweden, to the neighboring quartz porphyry is strikingly similar to the relation illustrated in the gravitatively differentiated laccoliths just mentioned (Fig. 204). Geijer considers that the Kiruna ore and quartz porphyry represent independent eruptions, probably extrusions.[2] On the other hand, none of the facts yet published is incompatible with the view that these Swedish ore-bodies are concentrations, in place, from the quartz porphyry body, whether that body is intrusive or extrusive. This conception should certainly be tested in the field.

It is not yet possible sharply to distinguish some magmatic ores from those which have been concentrated by aqueous solutions at low temperatures. Nevertheless, certain ores have clearly been segregated by *gaseous transfer* in molten magmas. Geijer describes an instructive example at Näsberget, Sweden. (See page 402.) Some of the magnetite bodies developed at the contact of limestone and intrusive rock have features suggesting pneumatolytic origin (Fig. 205). Further illustration of this topic may well be left to the standard works on ore-deposits.

[1] H. A. Brouwer, Oorsprong en Samenstelling der Transvaalsche Nephelien-syenieten, 's Gravenhage, 1910, pp. 9 and 28.

[2] P. Geijer, Geology of the Kiruna District (2), Stockholm, 1910, p. 269.

CHAPTER XXII

ECLECTIC THEORY APPLIED TO THE NORTH AMERICAN CORDILLERA

A review of facts detailed in the last seven chapters appears to give a certain sanction to the general theory. Those facts have been selected from a countless number concerning single igneous species, families, and clans throughout the world. Imperfect original descriptions and imperfect interpretation of map and printed page are obvious dangers to the investigator striving to find his way through the maze. Yet the writer feels the value of a mental scheme toward which the explanation of each of the rock clans in turn seems to point. He cannot believe that so many converging rays end in a kind of will o' the wisp leading one away from the main road to a correct geological philosophy. The honesty of the light is proven when the general theory matches all the interlocking observations to be made in a comprehensive eruptive area. That area must be large enough to include several of the so-called "petrographical provinces." Its close scientific analysis will reveal any vital weakness in the structure of the theory and will determine its prophetic value.

Even if the writer were able to make so full a comparison, his results could not be stated in one volume or two. However, space in the present one may be taken for an outline of some salient considerations affecting one of the ideal regions.

The motive which has impelled the writer to develop the general theory was supplied during nine years of work on the geology of the Cordilleran belt at the boundary between Canada and the United States. The correspondence between the theory and the many facts then discovered is considered in Memoir No. 38 of the Geological Survey of Canada (1912). The belt crosses a half-dozen large provinces, each of which bears intrusive and extrusive formations. Compiling the information derived from the boundary survey with that won from field work and laboratory studies in areas to the north and to the south, the writer will now apply the eclectic theory, point by point, to the North American Cordillera as a whole. Insufficient knowledge of the field must naturally involve some uncertainty in the result but, on the other hand, any systematic theory of petrogeny has its chief value in being a guide to the future increase of knowledge. The proposed system is so complex that a final illustrated summary, parallel to that in Chapter 14, may be helpful to the reader.

The igneous geology of the Cordillera is essentially like that of the general continental surface of the earth. It is the largest well-defined region of post-Huronian eruptivity, containing the greatest exposed batholith, the most extensive area of fissure eruption yet mapped, and one of the world's longest stretches of volcanic vents. All igneous-rock families and clans are represented. Excepting the granodiorites, the species are found in individual and total volumes roughly like those of similar areas in the other continents. In Washington's "Chemical Analyses of Igneous Rocks published from 1884 to 1900," 573 superior analyses of Cordilleran rocks are recorded. Adding to them 44 analyses made for the memoir on the geology of the international boundary, the writer has calculated the average silica percentage to be 59.97 (unreduced computation). This value is nearly identical with Clarke's average silica percentage calculated from the analyses of rocks of the whole world, and with that calculated by Harker from 536 analyses of British rocks.[1] Calculations of the other oxides would show corresponding similarity. Though containing several unknown geological and psychological factors, the Cordilleran, British, and World averages tend to strengthen belief that the earth is homogeneous in the very heterogeneity of its igneous products.

The existence of the *three principal earth-shells* below the Cordilleran surface is to be inferred from the structural geology. Beneath the *geosynclinal sediments* of Paleozoic and later dates is an acid pre-Cambrian terrane. Today, this outcrops in many places where erosion has denuded the tops of local upwarps. The former exposure of much larger areas of the acid pre-Cambrian terrane is proved by the composition of the "Beltian" and Paleozoic sediments in the Rocky Mountain geosynclinal, which sweeps from Mexico to Bering Sea. The quartzose character of the oldest pre-Cambrian sediments themselves, as exposed in British Columbia, Montana, Colorado, and Arizona, shows that the unknown lands from which these sediments were derived were of quartzose (probably granitic or gneissic) composition. Thus, as far back as we can yet penetrate into geological time, the surface formations of the Cordilleran region were highly silicious. Most of the visible pre-Cambrian basement is constituted of intrusive granite, exactly as in the Canadian and Fennoscandian shields. Evidently, therefore, the existing complex cannot be regarded as an original earth-shell. However, the argument of Chapter VIII, that the visible pre-Cambrian granites must essentially be the products of a remelted *acid earth-shell*, is as valid for the Cordilleran pre-Cambrian as it is for any other region of the

[1] See F. W. Clarke, Bull. 491, U. S. Geol. Survey, 1911, p. 25.

globe. The compelling reason for this belief is found in the composition of the ocean. That the conclusion applies to the Cordilleran section is suggested by the general similarity of the pre-Cambrian geology here and in the more extensive pre-Cambrian areas of the world.

The existence of a *continuous layer of eruptible basalt beneath the Cordillera* is to be inferred from facts of the kind noted in Chapter VIII. Those specifically applying in the present instance may be summarized under headings as follows:

1. *The clearly exotic nature of the Cordilleran basalts of all ages.* They have characteristically penetrated the pre-Cambrian basement and the overlying geosynclinals through narrow fissures in which important solution of the visible terranes was impossible.

2. *The equal impossibility of believing that these basalts are post-"Archean" differentiates of primary magma.* Nowhere in the Cordillera is there exposure of the complementary submagma expected on this hypothesis.

3. *The persistence and uniform composition of the basalts erupted during late pre-Cambrian and subsequent time.* There are no demonstrable chemical differences in the basalts which were actually erupted during the early pre-Cambrian (Shuswap series of British Columbia), and during the "Beltian," Cambrian, Carboniferous, Triassic, Jurassic, Eocene, Oligocene, Miocene, Pliocene, Pleistocene, and Recent periods.

4. *The general distribution of basaltic (gabbroid or diabasic) bodies throughout the Cordilleran region.* They are numerous in most of the states, provinces, and territories, from Alaska to Southern Mexico.

5. *The enormous volumes of the basalts issuing as fissure eruptions.* These are of many dates, including an early pre-Cambrian period (Shuswap series of British Columbia), the "Beltian" period (Unkar-Chuar group of Arizona), the Middle Cambrian? (49th Parallel), the Pennsylvanian (Southern British Columbia, etc.), the Triassic (Southern British Columbia, etc.), the Eocene (Washington), the Oligocene (British Columbia), the Miocene (Washington), and the Pliocene (Idaho, etc.). The mere size of those bodies does not, of course, prove the existence of a continuous substratum, but it makes any other published hypothesis of their origin extremely difficult of acceptance.

So far as it can be checked by field observations, the principle of *abyssal injection* seems to be verified in the Cordilleran geology. The thousands of basaltic, diabasic, or gabbroid dikes are the actual fillings of fissures which *must* extend to great depth, since the vast basaltic floods just noted have issued from fissures averaging less than 50 feet in width.[1] Temperature gradients in the region are generally

[1] See, for example, the Mount Stuart folio of the U. S. Geol. Survey.

normal in quality, implying a minimum depth of about 25 miles for the substratum.

That the lower part of this thick "crust" is subject to *tensional stresses or else is condensible under magmatic pressure* is quite clear. The proof is seen in the fact that these deep-reaching Cordilleran dikes are composed of material which cannot be essentially due to fluxing of the intruded (chiefly acid) rocks. No alternative explanation seems tenable.

Abyssal injection as stated in the eclectic theory involves a tendency to *downwarping* in the invaded zone. In spite of the relative impenetrability of the shell of compression, the magmatic material should occasionally work its way, through fissures in the downwarped area, to the earth's surface. Contemporaneous vulcanism is thus expected as an occasional event during the thickening of geosynclinal prisms. On page 186 will be found the table containing many actual examples which are taken from the Cordilleran geology. A few of these may be specially recalled. In the Hozomeen division of the Cascade range (see No. 9 in the table) the downwarp affected a Lower Cretaceous-Jurassic land-surface, which was deeply covered with volcanic breccias before the thick Cretaceous geosynclinal was deposited. Similarly, the erosion surface limiting the Pennsylvanian limestones near Kamloops, British Columbia, is almost directly covered by the thick basaltic extrusions of the Triassic (Nicola group). The thick Tertiary basalts of Oregon rest on an eroded mountain range, the surface of which, at the Columbia river, has been downwarped well below sealevel. Is it possible to believe that the crustal deformation is thus again and again associated with vulcanism as a result of pure accident?

Many facts derived from the Cordilleran field prove *superheat in the primary basalt.* The narrowness and great height of the basaltic (and diabasic) dikes; the thinness, uniformity in thickness, and wide expanse of multitudes of basaltic lava flows, are all familiar to the geologist working in the "Belt terrane" of Montana, Idaho, and British Columbia, and in the lava fields of the northwestern United States or of Mexico.

The passage of superheated basalt through fissures must soon tend to cause limited *solution of the wall rocks.* Such is the preferred explanation of the quartz-bearing diabase found in many of the feeders of the Eocene (Teanaway) basalt eruptions in Washington State. Some of the Eocene flows themselves, like others of Miocene age (Yakima basalt), are similarly acidified.

Certain intrusive sheets of gabbro, injected from the main Teanaway fissures, carry interstitial micropegmatite. Similar material is found in dozens of the thick gabbroid sills in the silicious Belt terrane of the Purcell mountains and the neighboring ranges of Idaho and Montana. In general the acidification is proportionate to the thickness of each sill. In some of the thickest sills this silicious ingredient, so foreign to normal basaltic or gabbroid rock, has been assembled by gravity into distinct layers. Its mean chemical composition is then determinable with some nicety. In the Purcell sills it is nearly identical with that of the invaded feldspathic quartzites, which are relatively uniform through a great vertical range and may be chemically averaged. The similarity between acid igneous phase and quartzite also extends to mineralogical composition. In very few other regions are the conditions so favorable for testing the hypothesis that thick injections of basalt normally assimilate their country rocks. The Purcell sills clearly confirm that view and other Cordilleran sills, also discussed in Chapter XVI, illustrate its truth.

The horizontal extension of an individual sill in the Cordilleran region seldom, if ever, approaches that of one of the greater South African sills, but, as in those cases, proves *the ability of magma to migrate laterally* from the feeding fissure for long distances. The great areas of these sills in ground plan go far to strengthen belief that the wide gabbro masses in western Oregon (Roseburg-Port Orford region) and the still vaster ones in Minnesota, Wisconsin, South Africa, etc., are of laccolithic origin and are definitely floored. Such bodies are liable to break through their roofs and initiate *"subordinate" volcanoes*, contrasted with the *"principal" volcanoes* which are situated on the main abyssal wedges. The principle of horizontal migration of magma is also of great importance in the question as to the origin of certain eruptive rocks.

Though not the longest on record, the Cordilleran basaltic dikes include many which are in *length of the same order as ordinary batholiths.* Hence, so far as that dimension is concerned, the existence of dikes—the visible magmatic wedges—tends to corroborate the idea that batholiths are thick magmatic wedges, chemically and physically modified because of their own great supply of heat.

The eclectic theory holds that the greatest wedges are *injected from the substratum during or immediately after energetic mountain building.* The Cordilleran batholiths have, in fact, been intruded at such epochs; the writer knows of no exception to the rule. (See Table VI, page 98.)

Usually the batholiths should be intruded along or near the axis of the mountain chain, there to solidify as "central" granite. Strong overthrusting ("charriage") may, however, transfer a large part of a folded geosynclinal to a new position outside the axial zone; in that case batholithic masses are not necessarily expected in the overthrust block. This principle may possibly explain the absence of batholiths in the Rocky Mountains (proper) of Canada and northern Montana.

An abyssal wedge composed of superheated basalt and of batholithic size must stope down the roof and wall rocks and dissolve them. Stoping is admirably illustrated in practically all the batholithic provinces of the Cordillera—the Alaska-British Columbia Coast Range, the West Kootenay province, the Idaho batholith, the Boulder batholith of Montana, the large stocks of Colorado, the Sierra Nevada, etc. It was in the Cordilleran region, at Marysville, Montana, that Barrell independently invented the *stoping theory of magmatic emplacement* and there also that the writer, working along the 49th Parallel, became convinced of its value.

Its most important corollary—*abyssal assimilation and the large-scale development of secondary magmas*—cannot, by its very nature, be directly proved in the field. The principle of inference is here paramount. Cordilleran geology is amply charged with facts which seem to enforce belief in a positive inference, for most of the non-basaltic rocks in the mountain chain. A full statement is now clearly impossible, since it ought to be quantitative and should consider the relative and absolute volumes of the different bodies of rock. Nevertheless, the folios of the United States Geological Survey furnish convenient samples of the Cordilleran igneous geology with a fair approach to quantitative description for as many local areas. In the writer's opinion, their synthetic study tends to corroborate the assimilation theory.

Confidence in the described explanation of the Cordilleran batholiths is notably strengthened by the *eruptive sequences* already demonstrated in these mountains. The batholithic sequences are orderly, as shown in Appendix B. Where field work has been appropriate and sufficiently extended, the order of eruption is found to pass from basic to acid. The initial product is generally rock of basaltic composition, either in volcanic masses or intrusive as dikes, sheets, chonoliths, etc. Then follow the granitic rocks of acidity that normally increases during successive intrusions, with aplitic types as the final term of the series. The eruptive sequence in a given area may, of course, be complicated by the independence of activity in neighboring magmatic wedges. These may assimilate contrasting kinds of country rocks, at contrasting rates, and in contrasting amounts; in addition, the syntectic magmas may undergo differentiation with contrasting results. In view of so many disturbing factors, it is highly significant that the general rules above mentioned are well observed in apparently all the greatest batholithic fields of the Cordillera—in Alaska, British Columbia, Washington, Idaho, Montana, and California. The rules also apply to the different petrogenic cycles registered in a single area, as in southern British Columbia, where pre-Cambrian, Jurassic, and Tertiary cycles are all represented on a large scale.

Again, the assimilation theory demands that the batholithic magma should vary *chemically with the nature of the country rocks.* This principal test has been discussed in Chapter XI and succeeding chapters, where illustrations are largely taken from the Cordillera of North America. The facts need not be repeated. The reader may refer to the pages dealing with the quartz diabases, quartz gabbros, hornblende gabbros, quartz basalts, granites (normal and abnormal), diorites, quartz diorites, andesites, granodiorites, dacites, quartz monzonites, monzonites, latites, syenites, trachytes, sodalite syenites, foyaites, and the nephelitic, analcitic, and leucitic rocks in general. Not all of these Cordilleran types were developed in batholithic chambers; many of them are formed in smaller ones, including sills and other injections from abyssal magmatic wedges.

In the Cordillera, as elsewhere in the world, *intrusive sheets have extraordinary meaning for petrogenic theory.* We have just noted that these lend indirect but powerful support to the assimilation doctrine as applied to the primary wedges.

Thus, four chief kinds of evidence—magmatic replacement (incorporation) by batholiths, the eruptive sequence in batholithic regions, the systematic chemical variation in batholiths, and the testimony of floored injections— seem to show that abyssal assimilation is one of the three fundamental processes by which batholiths and stocks have been formed.

After abyssal basaltic injection and assimilation, the remaining principle, *magmatic differentiation,* is logically considered. This does not mean, of course, that the two secondary processes are so separated in time. In general, the solution of foreign material in magma inevitably tends to produce some immediate differentiation. However, many facts derived from the Cordilleran batholiths and stocks show that *differentiation continues long after significant assimilation* of the country rock is impossible. For example, the wide stoping breccia bordering the batholith at Trail, British Columbia, is composed of sharp-angled, basic xenoliths, which suffered no essential amount of corrosion by the including granodiorite magma. This magma is a differentiate and has itself continued to split, locally, into aplitic and vogesitic submagmas. (See page 366.)

More than a score of the Cordilleran sills and laccoliths show *gravitative differentiation.* (See Table XIV, page 230.) Bodies of this type have the right of way in the discussion of magmatic splitting; their significance is out of all proportion to the number of such injections actually recorded. More clearly than any other eruptives they are witness to the certain control of gravity in the differentiation of batholithic syntectics. The extent of that control in batholiths is, however, chiefly to be inferred from the observed eruptive sequence. Another indirect evidence is found in the frequently observed contrast between a plutonic rock in the Cordillera and its corresponding effusive phase. On the average, the former is the more femic and magmatically was of higher specific gravity. This contrast is found, for example, between the effusive dacites and the syngenetic granodiorites of the western half of the mountain chain. Though clearly of batholithic origin, the Yellowstone Park rhyolite is more salic than the average granite or quartz monzonite of the neighboring Boulder batholith which, in its comparatively recent date, structural relations, and chemical habit, is so suggestively allied to the Park rhyolite.

The more subordinate *control of gaseous transfer in differentiation* is abundantly illustrated by many intrusive bodies in British Columbia, Montana, California, etc. (See pages 320, 361, 368, 452, and 455.)

No other mountain chains more tellingly illustrate the *relation between size of the magmatic chamber and the advance of differentiation.* Examples are described in Chapters XVI and XX, pages 344, 363–6, and 428. In spite of many complications, the facts observed in Montana, British Columbia, New Mexico, etc. point in the direction indicated by the eclectic theory, which also accounts for the existence of basic contact phases occurring in numerous intrusive bodies of the western mountains. (See pages 237, 366, and 390.) The laccoliths of the Highwood Mountains, Montana, furnish standard illustrations of gravitative splitting and the formation of peripheral basic phases by contact chilling; they also prove the high liquidity and strong tendency to differentiation characteristic of at least some alkaline magmas.

The eclectic theory recognizes *two kinds of differentiation of primary basalt* which has not been specially affected by syntexis.

Under certain little-understood conditions, intrusions of this magma split gravitatively, *with anorthosite as the salic pole.* Cordilleran geology has, so far, little to offer on this question, but it has abundant illustrations of the other mode of splitting, that at volcanic vents of the central type.

The more salic and more voluminous submagma is here a *pyroxene andesite.* Theory demands that this andesite shall often be transitional into normal basalt, as so frequently observed in the Cordilleran field. Theory expects that this andesite, while very abundant throughout the world, shall not constitute great fissure eruptions like the basaltic floods. Our Cordillera clearly matches this deduction as it does the related deduction that pyroxene andesite should show evidence of low temperature at eruption. Under normal conditions, intrusive basaltic magma is rather stubborn in refusing to differentiate. The homogeneity of diabase and gabbro in most dikes and sills and in many laccoliths and chonoliths, independently of size or geological age, is exactly a feature to be expected if basalt is itself a primitive differentiate of earth magma. Such a solution should early be brought to chemical equilibrium under subsurface conditions. Evidently those conditions are altered in a volcanic pipe through which concentrated gas is streaming. The basalt there differentiates at a relatively low temperature. The andesitic submagma may issue in the form of a true flow but its high viscosity, coupled with periodic freezing of the vent, should more generally lead to explosion and the formation of pyroclastic deposits. The Cordilleran andesites seem, in fact, to be chiefly pyroclastic, in formations that date from the pre-Cambrian to the Pleistocene. They outcrop at intervals, throughout the whole length of the Cordillera.

Structural geology and existing topography show that the andesitic volcanoes of the Cordilleran belt have been habitually *erected in lines roughly parallel to geosynclinal and orogenic axes.* Their arrangement is intelligible on the assumption that they have been local vents from primary basaltic wedges in theoretically appropriate relation to downwarp and mountain range.

The eclectic theory is thus capable of explaining the dominance of pyroxene andesites among the products of the Cordilleran volcanoes of the central type, as well as the dominance of basalt in the spectacular fissure eruptions of the northwestern United States.

In the Cordillera, as in any of the major subdivisions of the earth's surface, *basaltic types dominate among extrusives, and acid differentiates dominate among the visible intrusive masses*—a fundamental fact which itself goes far toward corroborating the general theory.

In Cordilleran bodies, both extrusive and intrusive, *alkaline species are of very small volume as compared with the subalkaline species*, whether individual masses or total quantity be considered. This is yet another of the geological truths which have been too little regarded by petrologists.

The foregoing brief sketch of the huge western field carries no direct mention of many important points which are discussed in earlier chapters. However, it is already evident that the North American Cordillera is rich in illustrations of nearly every phase of igneous geology. The continued study of this regional unit, with its stimulating variety and admirable exposure of eruptive rocks, has the raw material for a complete petrogenic theory of the world. It is not probable that either Europe or any other continent can afford as many *fruitful* facts during the coming century of petrological research. Those compiled to test the eclectic theory appear to support it in general, but the writer's chief purpose in elaborating the theory is to break ground for a better statement of igneous-rock philosophy for our Cordillera and for the earth.

APPENDIX A

TABLE XX.—SHOWING THE NUMBER OF SEPARATE DETERMINATIONS USED IN COMPUTING THE AVERAGE QUANTITY OF EACH OXIDE IN THE ROCK-TYPES LISTED IN TABLE II. (See page 19.)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SiO_2	47	114	184	236	64	24	40	50	20	12	6	13	7	2
TiO_2	22	74	60	87	40	10	30	20	12	7	4	5	6	2
Al_2O_3	47	114	180	232·	63	23	40	49	20	11	6	13	7	2
Fe_2O_3	35	101	118	158	61	22	39	32	11	9	5	10	6	2
FeO	35	101	118	158	42	6	36	32	11	9	5	10	6	2
MnO	24	86	64	93	32	4	28	20	5	6	1	6	7	..
MgO	47	114	184	236	63	24	39	49	20	12	6	13	7	2
CaO	47	114	184	236	64	24	40	49	20	11	6	13	7	2
Na_2O	47	108	182	234	63	24	39	49	20	12	6	13	7	2
K_2O	47	108	182	234	63	24	39	49	20	12	6	13	7	2
H_2O	38	40	41	41	17	15	17	39	14	10	3	10	5	2
P_2O_5	15	34	73	81	27	4	23	17	5	2	3	4	5	1

	15	16	17	18	19	20	21	22	23	24	25	26	27	28
SiO_2	2	11	50	48	10	7	5	8	5	23	19	7	12	3
TiO_2	1	9	35	26	4	5	4	5	5	14	7	6	4	..
Al_2O_3	2	11	49	48	10	7	5	8	5	23	19	7	12	3
Fe_2O_3	2	10	43	38	6	4	5	3	5	15	15	7	12	3
FeO	2	10	43	38	6	4	5	3	5	14	15	6	12	2
MnO	1	8	38	34	4	4	5	5	5	14	7	1	4	..
MgO	2	11	50	48	10	6	5	8	5	22	18	7	12	3
CaO	2	11	50	48	10	6	5	8	5	22	19	6	12	3
Na_2O	2	11	50	48	10	6	5	8	5	22	19	7	12	3
K_2O	2	11	50	48	10	6	5	8	5	21	19	7	12	3
H_2O	1	8	41	44	10	7	3	8	5	21	8	7	6	3
P_2O_5	1	8	34	25	3	3	3	....	4	7	6	4	3	1

	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
SiO_2	7	12	10	10	3	3	43	25	4	8	5	20	12	30	20	89	70
TiO_2	3	10	10	4	...	3	30	16	...	3	3	19	12	15	16	71	57
Al_2O_3	7	12	10	10	3	3	43	25	4	8	5	20	12	30	20	89	70
Fe_2O_3	6	12	10	6	3	3	30	18	2	2	4	20	12	24	18	86	69
FeO	6	12	10	6	3	2	30	18	2	2	4	19	12	24	18	86	69
MnO	3	10	10	4	3	2	30	15	1	3	1	20	12	14	11	66	53
MgO	7	12	10	10	3	3	41	25	4	8	5	20	12	30	20	89	70
CaO	7	12	10	10	3	3	43	25	4	8	5	20	12	30	20	89	70
Na_2O	7	12	10	10	3	3	43	25	4	8	5	20	12	30	20	85	67
K_2O	7	12	10	10	3	3	43	25	4	8	5	20	12	30	20	85	67
H_2O	6	9	10	10	3	1	26	23	4	6	5	20	12	30	17	47	36
P_2O_5	3	12	10	4	...	3	14	15	...	1	2	19	12	15	15	71	57

	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62
SiO_2	87	33	20	24	10	7	41	198	161	20	17	11	9	24	17	5	2
TiO_2	51	16	13	13	9	6	26	132	113	13	6	5	8	16	10	4	2
Al_2O_3	87	33	20	24	10	6	41	197	160	20	17	11	9	24	17	4	2
Fe_2O_3	71	25	18	18	10	7	36	174	146	18	14	5	9	21	15	5	2
FeO	71	25	18	18	10	7	36	173	146	18	14	5	8	21	15	5	2
MnO	44	16	14	8	6	6	28	108	96	13	6	2	4	15	13	4	2
MgO	87	33	20	24	10	7	40	197	160	20	17	11	9	24	16	5	2
CaO	87	33	20	24	10	7	41	198	161	20	17	11	9	24	17	5	2
Na_2O	84	32	20	22	10	7	40	190	154	20	16	11	9	24	16	5	2
K_2O	84	32	20	22	10	7	39	190	154	20	16	11	9	23	16	5	2
H_2O	57	5	18	24	10	6	17	55	27	16	1	5	2	12	5	4	2
P_2O_5	47	14	13	11	9	6	27	135	116	14	6	4	9	16	11	4	2

	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
SiO_2	12	3	7	5	5	5	6	31	14	4	10	3	20	34	14	6	6	6
TiO_2	4	3	4	4	...	1	6	13	8	4	6	3	20	25	11	3	2	6
Al_2O_3	12	3	7	5	5	5	4	29	14	4	10	3	19	34	14	6	6	6
Fe_2O_3	10	3	7	5	2	4	4	28	14	4	10	3	19	31	11	5	6	6
FeO	10	3	7	5	2	4	5	29	14	4	10	3	19	31	11	5	6	6
MnO	3	1	3	4	2	4	2	21	7	4	8	3	13	14	5	...	4	4
MgO	12	3	7	5	5	5	6	31	14	4	10	3	20	34	14	6	6	6
CaO	12	3	7	5	5	5	4	29	14	4	10	3	20	34	14	6	6	6
Na_2O	12	3	6	3	...	3	2	17	13	2	7	3	20	34	13	6	6	6
K_2O	12	3	6	3	...	2	1	15	13	1	6	3	20	34	13	6	6	6
H_2O	7	3	6	4	5	5	6	29	14	4	9	3	20	22	11	4	6	6
P_2O_5	1	1	3	3	...	1	2	12	9	4	6	3	16	29	9	2	2	6

	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97
SiO_2	24	20	4	20	16	4	1	2	7	7	6	2	9	26	5	5	3
TiO_2	8	14	4	4	11	3	1	2	2	6	6	2	3	23	5	5	3
Al_2O_3	24	20	4	20	16	4	1	2	7	7	6	2	9	26	5	5	3
Fe_2O_3	22	19	3	19	15	4	1	2	4	5	6	2	3	25	5	4	3
FeO	22	19	3	19	15	4	1	2	4	5	6	2	3	25	5	4	3
MnO	14	7	1	13	5	2	1	2	1	4	6	...	4	15	4	1	3
MgO	24	20	4	20	16	4	1	2	7	7	6	2	9	26	5	5	3
CaO	24	20	4	20	16	4	1	2	7	7	6	2	9	26	5	5	3
Na_2O	24	20	4	20	16	4	1	2	7	7	6	2	9	26	5	5	3
K_2O	24	20	4	20	16	4	1	2	7	7	6	2	9	26	5	4	3
H_2O	9	18	3	6	15	3	1	2	3	4	5	2	5	25	4	4	3
P_2O_5	19	9	3	16	8	1	1	2	5	2	5	2	6	23	5	4	3

	98	99	100	101	102	103	104	105	106	107
SiO_2	10	4	10	20	4	8	5	2	15	5
TiO_2	10	4	9	20	4	8	5	2	9	2
Al_2O_3	10	4	10	20	4	8	5	2	15	5
Fe_2O_3	10	4	10	20	4	8	5	2	11	2
FeO	10	4	10	20	4	8	5	2	10	2
MnO	10	1	10	19	4	8	5	2	8	1
MgO	10	4	10	20	4	8	5	2	15	4
CaO	10	4	10	20	4	8	5	2	15	5
Na_2O	10	4	10	20	4	8	5	2	15	5
K_2O	10	4	10	20	4	8	5	2	15	5
H_2O	10	4	10	10	4	8	5	2	11	2
P_2O_5	10	4	9	16	4	8	5	2	7	......

	108	109	110	111	112	113	114	115	116
SiO_2..........	5	8	15	10	20	4	15	16	6
TiO_2..........	3	7	9	8	16	4	10	12	5
Al_2O_3.........	5	8	15	10	19	4	15	16	6
Fe_2O_3.........	4	8	10	8	16	4	10	14	5
FeO..........	3	8	9	8	16	4	10	14	5
MnO	4	8	9	7	17	1	8	9	2
MgO.........	5	8	15	10	20	4	15	16	6
CaO..........	5	8	15	10	20	4	15	16	6
Na_2O.........	5	8	15	10	20	4	15	15	5
K_2O..........	5	8	15	10	20	4	15	15	5
H_2O..........	3	7	10	10	19	4	10	16	3
P_2O_5..........	......	7	5	7	18	4	6	11	3

APPENDIX B

TABLE XXI.—SHOWING ORDER OF ERUPTION, FROM OLDER TO YOUNGER

(See Page 55.)

(Horizontal lines represent unconformities or other long time-intervals.)

PRE-CAMBRIAN SERIES

Saguenay District, Quebec (F. D. Adams, Neues Jahrbuch für Mineralogie, etc. B. B. 8, 1893, p. 464):

1. Greenstone, amphibolite (basic lavas); orthogneiss.

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2. Gabbro, anorthosite, norite.
3. Pegmatite.
4. Diabase, augite porphyrite.

Long Lake Quadrangle, Adirondacks (and vicinity) (H. P. Cushing, Bull. 115, New York State Museum, 1907):

1. Gabbro, amphibolite.
2. Orthogneiss.

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3. Gabbro, anorthosite.
4. Syenite.
5. Granite.
6. Gabbro.
7. Diabase.

North Central Wisconsin (S. Weidman, Bull. 16, Geol. and Nat. Hist. Survey of Wisconsin, 1907):

1. Greenstone (diabase, gabbro, etc.).
2. Granite, quartz syenite.

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3. Rhyolite, rhyolite-andesite.
4. Gabbro, diorite, troctolite.
5. Granite, quartz syenite, nephelite syenite, mica syenite, pegmatite.

Lake Superior District (C. R. Van Hise and C. K. Leith, Monograph 52, U. S. Geol. Survey, 1911):

A. *Keewatin:* Greenstone (basalt and andesite), quartz porphyry, rhyolite, felsite, diorite.
B. *Laurentian:* Granite, syenite, orthogneisses.

C. *Post-Lower-Middle Huronian:* Granite, syenite, nephelite syenite, gabbro, diorite, rhyolite.

D. *Upper Huronian:* Gabbro, diabase, basalt, diorite, felsite.
E. *Post-Upper Huronian:* Granite.

F. *Keweenawan:* Olivine gabbro, gabbro, norite, olivine norite, quartz norite, quartz gabbro, diorite, quartz diorite, diabase, orthoclase gabbro, granite, soda granite, syenite, monzonite, trachyte, rhyolite, quartz keratophyre, quartz diabase, augite andesite, basalt, hypersthene diabase, troctolite, pyroxenite, peridotite, plagioclasite.

Sweden in general (A. G. Högbom, Bull. Geol. Inst. Univ. Upsala, Vol. 10, 1910):

A. *Lower Pre-Cambrian:*

1. Orthogneiss, granite, leptite, amphibolite, uralite porphyrite, diorite, gabbro, syenite, etc.
2. Diabase.
3. Granite.

B. *Middle Pre-Cambrian:* Greenstone ("basic").

C. *Subjotnian:* Granite, syenite, gabbro, anorthosite, etc.

D. *Upper Pre-Cambrian (Jotnian):* Diabase, olivine diabase.

Kiruna District and Vicinity, Sweden (P. Geijer, Geology of the Kiruna District, Part 2, Stockholm, 1910; H. Lundbohm, Geol. För. Stockholm Förhand., March, 1910):

1. Diabase.
2. Soda greenstone.
3. Alkaline syenite and syenite porphyry.
4. Alkaline quartz porphyry, magnetite ore (eruptive).

Finland (J. J. Sederholm, Bull. Commission Géol. de Finlande, No. 23, 1907; for revised statements see No. 24, 1910, and No. 28, 1911.)

A. *Katarchean:* Granite, "metabasite" (altered diabase, etc.).

B. *Ladogian:* "Metabasite."

C. *Post-Ladogian:* Granite, diorite, amphibolite, etc.

D. *Bottnian:* Uralite porphyrite, plagioclase porphyrite, etc.

E. *Post-Bottnian:* Granite.

F. *Lower Kalevian:* "Metabasite."

G. *Upper Kalevian:* "Metabasite."

H. *Post-Kalevian:* Granite.

I. *Lower Jatulian:* "Metabasite."

J. *Upper Jatulian:* Augite porphyrite, "metabasite."

K. *Jotnian:* Diabase, "labradorite," granite (Rapakivi).

General Series

Southern British Columbia (R. A. Daly, Mem. 38, Geol. Surv. Canada, 1912):

A. *Pre-Cambrian:*

1. Greenstone (basalt, basic andesite), diabase, diabase porphyrite, etc.
2. Granite, pegmatite.

B. *Cambrian* (?): Gabbro, basalt, abnormal sill granites.

C. *Carboniferous* (Pennsylvanian):
1. Basalt, augite andesite, basic greenstone.
2. Dunite, serpentine.

D. *Triassic:* Basalt, basaltic andesite.
E. *Jurassic:*
1. Gabbro, diorite.
2. Granodiorite, quartz monzonite.
3. Biotite granite, aplite.

F. *Cretaceous* (*Knoxville*): Augite andesite.

G. *Eocene* (?): Basalt and augite andesite of Selkirk range; nephelite syenite and malignite of Okanagan range.
H. *Oligocene* (Midway district):
1. Basalt, augite andesite.
2. Mica andesite, hornblende andesite.
I. *Miocene:*
1. Granodiorite and diorite of Selkirk, Okanagan, Hozomeen and Skagit ranges; pulaskite of Rossland mountains; monzonite of Selkirk range.
2. Syenite porphyry of Rossland mountains, and of Columbia, Hozomeen and Skagit ranges; rhomb-porphyry and "shackanite" (an analcitic lava) of Columbia range; alkaline granite of Okanagan range.

J. *Pliocene:* Basalt dikes of Okanagan range.
K. *Pleistocene:* Pyroxene andesite of Mount Baker (Wash.).

New Mexico (W. Lindgren, L. C. Graton and C. H. Gordon: Prof. Paper 68, U. S. Geol. Survey, 1910, p. 26 and sequel):
A. *Pre-Cambrian:*
1. Greenstone, amphibolite, rhyolite.
2. Granite.
3. Aplite, pegmatite, diorite.

B. *Tertiary:*
1. Monzonite, quartz monzonite, granodiorite, diorite, and porphyries of similar composition.
2. Basalt, rhyolite.
3. Andesite, basaltic andesite, latite, trachyte.
4. Rhyolite.
C. *Quaternary-Recent:* Olivine basalt, nephelite basalt, phonolite (last two Tertiary?).

Globe Quadrangle, Arizona (F. L. Ransome, Prof. Paper 12, U. S. Geol. Survey, 1903):

A. *Pre-Cambrian:*

1. Quartz-mica diorite.
2. Two-mica granite and muscovite granite.
3. Biotite granite (Diabase older than No. 3).

B. *Mesozoic:*

1. Diabase.
2. Diorite porphyrite.

C. *Tertiary:* Dacite.

D. *Quaternary:* Basalt.

British Isles (A. Geikie, Quart. Jour. Geol. Soc. London, Pres. Address, Vol. 47, 1891, p. 63; T. C. Cantrill and H. H. Thomas, Ibid., Vol. 62, 1906, p. 250):

A. *Pre-Cambrian:*

a. *Lewisian:* Granite, diorite, gabbro, pyroxenite, hornblendite, peridotite, picrite, syenite.

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b. *Post-Lewisian of Scotland*, in the following order:

1. Dolerite.
2. Peridotite, picrite.
3. Granite, syenite, pegmatite.

c. *Uriconian of Wales and Shropshire:* Rhyolite, felsite, microgranite, diabase, greenstones.

B. *Cambrian:*

Bangor district:

1. Rhyolite, quartz porphyry, felsite.
2. Andesites, rhyolite.

St. David's area: Diabase, olivine diabase, rhyolite (felsite).

C. *Silurian:*

a. *Arenig:*

1. Augite andesite.
2. Rhyolite.
3. Augite andesite, hornblende andesite.
4. Diabase, porphyry.

b. *Llandeilo and Bala:*

Caernarvonshire:

1. Rhyolite, andesite.
2. Diabase.

Anglesey: Rhyolite (felsite), dolerite.

Lake District:

1. Andesite, basaltic andesite, gabbro, diabase, granite.
2. Rhyolite.

Scotland: Diabase, felsite, andesite (?).

Ireland: Felsite, andesite, diorite, quartz diorite, microgranite, diabase, dolerite.

D. *Old Red Sandstone:*
  a. *Lower Old Red Sandstone:* Olivine diabase, diabase, augite andesite, trachyte, granite, quartz diorite, minette, vogesite.
  b. *Upper Old Red Sandstone:* Diabase, porphyrite.

Devonian: Dolerite, diabase.

E. *Carboniferous* (Scotland):
  a. Plateaus: Dolerite, olivine basalt, andesite, picrite, limburgite, trachyte, phonolite, felsite.
  b. Puys: Olivine basalt, basalt, dolerite, andesite, picrite, limburgite, felsite, quartz porphyry.

F. *Permian:* Basalt, picrite.

G. *Tertiary:*
  1. Basalt, olivine dolerite, gabbro.
  2. Rhyolite, felsite, dacite, granophyre, granite, pitchstone.

Germany (R. Lepsius, Geologie von Deutschland, 2 Lief., Stuttgart, 1887–1910):

A. *Grundgebirge* (all pre-Cambrian?): Granite, orthogneisses, pegmatite, diorite, gabbro, amphibolite, granite porphyry, minette, kersantite, alsbachite, malchite.

B. *Cambrian* (Lower Rhine Region): Diabase, quartz porphyry, "porphyroid."

C. *Silurian* (Lower Rhine Region): "Porphyroid."

D. *Devonian* (Lower Rhine Region):
  1. Lower Devonian: "Porphyroid."
  2. Middle Devonian: Diabase, diabase porphyrite.
  3. Upper Devonian: Diabase, diabase porphyrite.

E. *Carboniferous to Permian (inclusive)*: Melaphyre, diabase, olivine diabase, augite porphyrite, gabbro, granite, granite porphyry, quartz porphyry, syenite.

F. *Tertiary (Miocene)*:
  Lower Rhine Region: Olivine basalt, basalt, trachyte, hornblende basalt, hornblende andesite, augite andesite, nephelite basalt, phonolite.
  Upper Rhine Region: Olivine basalt, basalt, trachyte, hornblende basalt, tephrite, limburgite, melilite basalt, nephelite basalt, leucite-nephelite basalt, phonolite.

G. *Quaternary* (Lower Rhine Region): Basalt, leucite basalt, nephelite basalt, trachyte, phonolite, leucite phonolite.

Japan (Compiled by the officials of the Imperial Geol. Survey of Japan, Tokio, 1902):

A. *Pre-Cambrian:* Granite, granulite, amphibolite, serpentine.

B. *Paleozoic:* Gabbro, diabase, porphyrite, amphibolite, peridotite, pyroxenite, serpentine.

C. *Triassic:* Porphyrite.
D. *Jurassic:* Porphyrite.
E. *Cretaceous:* Gabbro, diabase, diorite, porphyrite, peridotite, granite, quartz porphyry.

F. *Tertiary:* Basalt, pyroxene andesite, mica-hornblende andesite, dacite, liparite.
G. *Quaternary:* Basalt, basaltic andesite, augite andesite.

POST-CAMBRIAN SERIES

Belknap Mountains, New Hampshire (L. V. Pirsson, Amer. Jour. Science, Vol. 22, 1906, p. 507):
1. Granite.

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2. Syenite.
3. Aplite, camptonite, spessartite, essexite.
4. Camptonite, aplite.

Red Hill, New Hampshire (L. V. Pirsson and H. S. Washington, Amer. Jour. Science, Vol. 23, 1907, p. 446):
1. Granite.

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2. Nephelite syenite.
3. Aplite, paisanite, bostonite, syenite porphyry, camptonite.

Tripyramid Mountain, New Hampshire (L. V. Pirsson and W. N. Rice, Amer. Jour. Science, Vol. 31, 1911, p. 288):
1. Granite.

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2. Gabbro.
3. Monzonite.
4. Syenite.
5. Aplite.

Ascutney Mountain, Vermont (R. A. Daly, Bull. 209, U. S. Geol. Survey, 1903, p. 36):
1. Gabbro, diorite, acid essexite.
2. Nordmarkite, umptekite, monzonite.
3. Camptonite, paisanite.
4. Alkaline biotite granite.
5. Diabase.

Penobscot Bay Quadrangle, Maine (G. O. Smith, E. S. Bastin, and C. W. Brown, Folio No. 149, U. S. Geol. Survey, 1907):
A. *Cambrian* (?): Diabase, trachyte, syenite, rhyolite, andesite, dacite.
B. *Silurian:*
   1. Pyroxene andesite.
   2. Basaltic andesite.
   3. Hornblende andesite.
   4. Rhyolite.

C. *Late Silurian or Devonian:*
  1. Gabbro, diabase, diorite.
  2. Granite.

Essex County, Massachusetts (C. H. Clapp, personal communication):

A. *Post-Ordovician* (?):
  1. Gabbro-diorite, granodiorite, quartz diorite, granite.
  2. Aplite.
  3. Diabase.

B. *Devonian* (?) *to post-Lower Carboniferous:* Quartz keratophyre, trachyte, dacite, andesite, bostonite.

C. *Post-Lower Carboniferous:*
  1. Pulaskite, umptekite, nordmarkite, nephelite syenite, alkaline granite.

Provisional statement of sequence.	2. Olivine diabase. 3. Sölvsbergite, tinguaite, vogesite, minette, camptonite, kersantite. 4. Diabase, with and without biotite. 5. Quartz porphyry and paisanite. 6. Diabase porphyrite.

D. *Triassic* (?): Diabase.

Crandall and Ishawooa Quadrangles, Wyoming (Absaroka folio, U. S. Geol. Survey, 1899):

A. *Eocene:* Hornblende andesite, hornblende-mica andesite, dacite, pyroxene-hornblende andesite.

B. *Neocene:*
  1. Hornblende-pyroxene andesite, pyroxene andesite, olivine-free basalt, basalt.
  2. Basalt, leucite-bearing basalt, orthoclase-bearing basalt.
  3. Hornblende-mica andesite, hornblende andesite, pyroxene andesite, basalt.
  4. Hornblende-pyroxene andesite, pyroxene andesite, olivine basalt.
  5. Basalt, with quartz phenocrysts.
  6. Rhyolite.

Rosita Hills, Colorado (W. Cross, 17th Ann. Rep. U. S. Geol. Survey, Part 2, 1896, p. 274 ff.):

A. *Pre-volcanic Period:*
  1. Granite.
  2. Diabase, peridotite, syenite.

B. *Volcanic Period:*
  1. Hornblende-mica andesite.
  2. Augite-biotite-hornblende andesite.
  3. Diorite.
  4. Dacite.
  5. Rhyolite.
  6. Biotite-augite andesite.
  7. Trachyte.

Ouray-Silverton Quadrangles, Colorado (U. S. Geol. Survey folios, 1905 and 1907): (Tertiary sequence).
1. Pyroxene andesite, latite. (San Juan tuff.)
2. Silverton series (in order):
    a. Pyroxene andesite.
    b. Rhyolite.
    c. Latite.
    d. Pyroxene andesite.
3. Potosi series: Quartz latite, rhyolite.
   (Diabase, cuts Jurassic; relation to volcanics not known.)

Livingston Quadrangle, Montana (Livingston folio, U. S. Geol. Survey, 1894):
1. Hornblende-mica andesite, other andesites.
2. Pyroxene andesite, hornblende-pyroxene andesite, basaltic andesite, basalt, trachytic rhyolite.
3. Rhyolite.
4. Basalt.

Elkhorn District, Montana (W. H. Weed and J. Barrell, 22nd Ann. Rep. U. S. Geol. Survey, Pt. 2, 1901, p. 420):
1. Gabbro and diorite.
2. Quartz-diorite porphyry.
3. Granite.
4. Aplitic granite.

Yellowstone Park-Snake River District (J. P. Iddings, Quart. Jour. Geol. Soc., London, Vol. 52, 1896, p. 606):
A. *Eocene* (Absaroka range):
    1. Hornblende andesite, hornblende-mica andesite, dacite.
    2. Hornblende-pyroxene andesite, pyroxene andesite.
    3. Andesitic basalt.
    4. Great Breccia, including types as in 1–3, with intrusions of dacite, gabbro, diorite, granite.

B. *Pliocene:*
    1. Basalt, rhyolite.
    2. Rhyolite of Yellowstone Plateau.
    3. Basalt of Snake River region.

Midway District, Southern British Columbia (R. A. Daly, Mem. 38, Geol. Survey, Canada, 1912):
A. *Carboniferous* (?):
    1. Basalt, pyroxene andesite.
    2. Dunite.

B. *Late Jurassic* (?):
    1. Gabbro, diorite.
    2. Granodiorite.

C. *Oligocene*:
    1. Olivine basalt, gabbro, augite andesite, augite porphyrite.
    2. Hornblende-augite andesite, biotite-augite andesite, biotite andesite.

D. *Miocene* (?):
 1. Alkaline trachyte, pulaskite porphyry.
 2. Rhomb-porphyry, "shackanite" (an analcitic lava).

Okanagan Range, British Columbia-Washington (R. A. Daly, Bull. Geol. Soc. America, Vol. 17, 1906, p. 363):

A. *Carboniferous* (?): Gabbro, amphibolite, dunite.

B. *Late Jurassic:* Granodiorite, gabbro.

C. *Eocene* (?): Nephelite syenite, alkaline syenite, malignite.

D. *Miocene* (?):
 1. Granodiorite.
 2. Alkaline biotite granite.

E. *Pliocene:* Olivine basalt.

Mount Stuart Quadrangle, Washington (Folio No. 106, U. S. Geol. Survey, 1904):

A. *Carboniferous* (?): Diabase.

B. *Pre-Tertiary:*
 1. Peridotite.
 2. Granodiorite.

C. *Eocene:* Basalt, gabbro.

D. *Miocene:*
 1. Hypersthene andesite.
 2. Basalt.

E. *Pliocene* (?): Rhyolite.

John Day Basin, Oregon (F. C. Calkins, Bull. Dept. Geol., Univ. California, Vol. 3, 1902, p. 170):

A. *Clarno Eocene:*
 1. Hornblende andesite.
 2. Basic pyroxene andesite.
 3. Quartz basalt.
 4. Rhyolite.

B. *John Day Miocene:*
 1. Trachyte (?).
 2. Andesite.
 3. Rhyolite.
 4. Andesite.

C. . . . .: Basalt.

D. *Mascall Miocene:*
 1. Rhyolite.
 2. Basalt.
 3. Rhyolite.

E. *Rattlesnake Pliocene:*
 Rhyolite.

San Luis Quadrangle, California (Folio No. 101, U. S. Geol. Survey, 1904):

A. *Pre-Jura-Trias:* Granite.

B. *Jura-Trais* (?): Olivine diabase, diabase, basalt, peridotite, pyroxenite.

C. *Cretaceous:*
1. Dacite, andesite.
2. Diabase.
3. Gabbro, peridotite, pyroxenite.

D. *Neocene:*
1. Rhyolite.
2. Pyroxene andesite.
3. Quartz basalt.
4. Olivine diabase.
5. Augite teschenite.

Sierra Nevada of California (Folios of the U. S. Geol. Survey, and H. W. Turner, Jour. Geol., Vol. 3, 1895, p. 385):

A. *Devonian or older:*
1. Pyroxene andesite.
2. Rhyolite.

B. *Carboniferous:* Diabase, diabase porphyrite, augite andesite, hornblende andesite, peridotite, pyroxenite, rhyolite.

C. *Jura-Trias:* In general, same types as in Carboniferous.
Redding quadrangle gives:
Triassic:
1. Ophitic basic andesite, augite andesite.
2. Rhyolite.

Jurassic: Pyroxene andesite.

D. *Jurassic or Early Cretaceous:*
1. Granodiorite, quartz diorite, gabbro, syenite, dacite porphyry, hornblendite.
2. Granite, aplite.

E. *Neocene:*
1. Rhyolite.
2. Basalt.
3. Hornblende-augite andesite.
4. Pyroxene andesite, latite.
5. Basalt.

F. *Quaternary:* Pyroxene andesite, basalt.

Berkeley Hills, California (*Tertiary sequence*). (A. C. Lawson and C. Palache, Bull. Department of Geol., Univ. of Cal., Vol. 2, 1902, p. 438):

A. *Lower Berkeleyan:*
1. Andesite.
2. Basalt.
3. Rhyolite.
4. Andesite.
5. Basalt.
6. Rhyolite.

B. *Upper Berkeleyan:*
1. Andesite.
2. Basalt.
3. Rhyolite.

4. Andesite.
5. Basalt.

C. *Campan:*
1. Andesite.
2. Rhyolite.
3. Basalt.

Goldfield District, Nevada (F. L. Ransome, Prof. Paper 66, U. S. Geol. Survey, 1909, pp. 90–91 and Pl. IV):

A. *Mesozoic:* Granite, quartz monzonite, syenite.

B. *Eocene* (?):
1. Rhyolite.
2. Latite.
3. Rhyolite.
4. Olivine basalt.
5. Biotite andesite, hornblende andesite, pyroxene andesite, dacite.
6. Dacite, andesite, vitrophyre.
7. Rhyolite.
8. Andesite.
9. Olivine basalt (quartz-bearing).
10. Rhyolite.
11. Olivine basalt.

Eureka District, Nevada (Mon. 20, U. S. Geol. Survey, 1892, p. 290):

Late Tertiary and Quaternary:
1. Hornblende andesite.
2. Hornblende-mica andesite.
3. Dacite.
4. Rhyolite.
5. Pyroxene andesite.
6. Basalt.

Clifton Quadrangle, Arizona (W. Lindgren, Clifton folio, U. S. Geol. Survey, 1905):

A. *Late Cretaceous or Early Tertiary:*
1. Granite porphyry, quartz monzonite porphyry, diorite porphyry.
2. Diabase.

B. *Tertiary:*
1. Rhyolite.
2. Basalt.
3. Pyroxene andesite.
4. Basalt.
5. Rhyolite.
6. Basalt.
7. Rhyolite.

Island of Skye (A. Harker, and C. T. Clough, The Tertiary Igneous Rocks of Skye, Glasgow, 1904, p. 433):

A. *Pre-Tertiary:* Gabbro, granite.

B. *Volcanic Phase (Eocene)*:
1. Basalt, olivine basalt, hypersthene basalt, augite andesite.
2. Trachyte, rhyolite, andesite, felsite.
3. Basalt.

C. *Plutonic Phase* (in general younger than B.):
1. Peridotite, "picrite," troctolite.
2. Gabbro.
3. Granite, granophyre, syenite, marscoite.

D. *Phase of Minor Intrusions* (in general younger than C.):
1. Basalt, granophyre, felsite, porphyry, trachyte.
2. Dolerite, olivine dolerite.
3. Peridotite, "picrite."
4. Trachyte, augite andesite.

Glen Coe, Scotland (C. T. Clough, H. B. Maufe and E. B. Bailey, Quart. Jour. Geol. Soc., Vol. 65, 1909, p. 615):

Old Red Sandstone Period:
1. Augite andesites.
2. Rhyolites and andesites.
3. Hornblende andesites.
4. Rhyolite.
5. Andesites and rhyolites.

Mont Dore, France (A. Michel Lévy, Bull. soc. géol. France, Vol. 18, 1890, p. 743):

(Sequence from mid-Pliocene to Recent):
1. Phonolite, phonolitic trachyte.
2. Rhyolite.
3. Basalt.
4. Andesite, basalt.
5. Acid tuffs.
6. Acid andesite, trachyte.
7. Augite andesite, tephrite.
8. Phonolite.
9. Basalt of plateaus.
10. Basalt.

Le Velay and le Mézenc, France (P. Termier, Bull. des serv. carte géol. France, No. 13, Vol. 2, 1890 and M. Boule, Ibid. No. 28, Vol. 4, 1892):

(Miocene sequence):
1. Basalt.
2. Trachyte, phonolite.
3. Augite andesite, trachydolerite.
4. Basalt.
5. Phonolite.
6. Basalt.

Cantal, France (M. Boule, Bull. des serv. carte géol. France, No. 76, Vol. 11, 1900).

A. *Miocene:*
1. Basalt, olivine basalt.
2. Trachyte, phonolite.
3. Augite andesite.

B. *Pliocene:*
  1. Andesite, trachyte.
  2. Augite andesite ("labradorite"), olivine basalt.
  3. Hornblende andesite, augite andesite, phonolite.
  4. Basalt of the plateaus, olivine basalt.

La Limagne, France (P. Glangeaud, Bull. des serv. carte géol. France, No. 123, Vol. 19, 1909):
A. *Lower Miocene:* Basalt, teschenite, tephrite, nephelinite, phonolite.
B. *Middle Miocene:* Olivine basalt, limburgite.
C. *Upper Miocene:* Olivine basalt.
D. *Lower Pliocene:* Basalt.
E. *Middle Pliocene:* Basalt.
F. *Upper Pliocene:* Basalt, tephrite.
G. *Pleistocene:* Basalt.

Westerwald, Germany (G. Angelbis, Jahrbuch preuss. geol. Landesanst., Vol. 3, 1883, p. xlv.):
1. Basalt.
2. Trachyte.
3. Hornblende andesite, augite andesite.
4. Basalt.

Siebengebirge, Germany (H. von Dechen, Geognostischer Führer in das Siebengebirge am Rhein, Bonn, 1861):
1. Trachyte.
2. Nephelite (?) basalt, trachyte.
3. Olivine basalt.

Bohemian Mittelgebirge (J. E. Hibsch, Tschermak's Min. u. Petrog. Mitt., Vol. 19, 1900, p. 493, and Führer für die geol. Exkursionen, Internat. Geol. Cong. 1903, Part 2; F. E. Suess, Bau und Bild Oesterreichs, 1903, p. 196):
A. *Cambrian:* Diabase, diorite.

B. *Carboniferous-Permian:* Melaphyre, granite, granite porphyry, quartz porphyry, aplite, lamprophyre.

C. *Upper Oligocene:*
  1. Basalt, phonolite.
  2. Feldspar basalt, nephelite basalt, leucite basalt, limburgite.
  3. Trachydolerite, haüynite tephrite, sodalite syenite, sodalite gauteite, sodalite porphyry.
  4. Essexite, camptonite, gauteite, bostonite, nephelite tephrite, leucite tephrite, nephelite basanite.

D. *Miocene* (?):
  1. Basalt.
  2. Trachyte.
  3. Phonolite.
  4. Tinguaite, eleolite porphyry.

Carpathians (V. Uhlig, Bau und Bild Oesterreichs 1903, p. 894):
A. *Upper Eocene:* Trachyte.
B. *First Mediterranean Stage:* Rhyolite.

C. *After first Mediterranean Stage:* Basic pyroxene andesite.
D. *Somewhat later:* Biotite-amphibole andesite.
E. *Sarmatic epoch:* Rhyolite.

Predazzo (W. Penck, Neues Jahrb. für Mineralogie, etc., B. B. 32, 1911, p. 341):
1. Porphyrite (augite andesite, often bearing olivine).
2. Melaphyre.
3. Monzonite.
4. Pyroxenite.
5. Quartz monzonite.
6. Monzonite aplite.
7. Syenite.
8. Quartz syenite.
9. Syenite aplite.
10. Bostonite.
11. Nephelite syenite.
12. Tinguaite porphyry.
13. Granite. (Probably follows the nephelite syenite.)
14. Aplite.
15. Camptonite.

Monzoni, Tyrol (O. von Huber, Jahrb. k. k. geol. Reichsanst., Vol. 50, 1901, p. 395):
1. Pyroxenite.
2. Monzonite.
3. Melaphyre, augitite.
4. Plagioclase porphyrite.
5. Granite.
6. Camptonite.
7. Liebnerite porphyry, orthoclase porphyry.

Eolian Islands (A. Bergeat, Abhand. k. bayer. Akad. der Wiss., Kl. 2, Vol. 20, 1899, p. 1):

Islands in general:

A. *Middle or late Tertiary to Middle Quaternary:*
  1. Basalt.
  2. Andesite.

B. *Late Quaternary to Present:* Acid andesite, liparite, dacite, basanite.

Lipari:
1. Basalt.
2. Andesite.
3. Cordierite andesite.
4. Liparite.

Vulcano:
1. Basaltic andesite.
2. Liparite.
3. Younger liparite.
4. Leucite basanite (Vulcanello).

Filicudi and Alicudi:
1. Basalt.
2. Augite andesite.

Christiania Region, Norway (W. C. Brögger, Zeit. für Krystallographie, Vol. 16, 1890):

1. Diabase, diabase porphyrite, augite porphyrite.
2. Laurvikite, mica syenite, laurdalite, rhomb-porphyry, ditroite, foyaite, tinguaite, minette.
3. Akerite.
4. Nordmarkite.
5. Soda-granite, hornblende granite, arfvedsonite granite, ægerite granite.
6. Biotite granite.
7. Diabase, diabase porphyrite.

Ekersund-Soggendal District, Norway (K. F. Kolderup, Bergens Museums Aarbog, Vol. 5, 1896, p. 183):

1. Norite, anorthosite.
2. Norite, gabbro-norite, quartz norite.
3. Monzonite, banatite.
4. Ilmenite norite, ilmenitite (perhaps older than some of the banatites).
5. Augite granite, aplite.
6. Diabase, olivine diabase.

Julianehaab District, Greenland (N. V. Ussing, Geology of the Country around Julianehaab, Greenland, Copenhagen, 1911, p. 318):

1. Diabase.
2. Essexite.
3. Alkaline syenite. } almost contemporaneous.
4. Alkaline granite. }

Martinique (A. Lacroix, La Montagne Pelée et ses eruptions, Paris, 1904, p. 22):

1. Basalt, augite andesite ("labradorite").
2. Augite andesite ("labradorite"), hypersthene andesite, dacite.

Krakatoa (R. D. M. Verbeek, Krakatau, Batavia, 1886):

1. Hypersthene andesite.
2. Basalt.
3. Hypersthene andesite.

Java and Madura (R. D. M. Verbeek and R. Fennema, Description géologique de Java et Madoura, Amsterdam, 1896, p. 38 ff.):

A. *Cretaceous:* Diabase, gabbro, quartzose porphyry.

B. *Eocene:* Diabase, andesite (with dioritic phases).

C. *Base of Miocene series:* Basalt, diabase, gabbro, pyroxene andesite.

D. *Lower Miocene:* Gabbro, pyroxene andesite, hornblende andesite, quartz-mica-hornblende andesite (dacite).

E. *Middle Neo-Tertiary:* Pyroxene andesite.

F. *Post-Tertiary:* Basalt, pyroxene andesite, leucitic rocks and phonolites.

New South Wales (C. A. Süssmilch, Geology of New South Wales, Sydney, 1911, p. 155):

Ordovician: Andesites.

Silurian: Rhyolites, andesites.

Devonian: Basalt, rhyolite, granite, tonalite, quartz-mica diorite, granodiorite, quartz porphyry, serpentine (peridotite).

Carboniferous: Granite, rhyolite, hypersthene andesite, granite porphyry, feldspar porphyry.
Permo-Carboniferous: Basalt, andesite, trachyte.

Eocene (?): Basalt, olivine basalt.
Miocene or *Lower Pliocene:* Basalt.
Pliocene:
1. Comendites and quartz trachytes.
2. Alkaline trachytes.
3. Phonolitic trachytes.
4. Andesites.

Canobolas Mts., New South Wales (C. A. Süssmilch and H. I. Jensen, Proc. Linnean Soc. New South Wales, Vol. 34, 1909, p. 170.):
1. Comendites, pantellerites, quartz trachytes.
2. Trachytes, phonolitic trachytes.
3. Basic andesites, augite andesite, alkaline basalt.
4. Melilite basalt.

New England Plateau, New South Wales (E. C. Andrews, Records Geol. Survey, New South Wales, Vol. 8, 1905, p. 20):
A. *Carboniferous:* Dolerite, trachyte, andesite, rhyolite.
B. *Permo-Carboniferous:*
1. "Lavas."
2. Granite porphyry.
3. Granite.
4. "Eurite" (aplite).
5. Rhyolite, acid porphyry.
6. Diorite, hornblende and mica lamporphyres.

C. *Tertiary:* Basalt, pitchstone.

Victorio State, Australia (E. W. Skeats, Pres. Address, Austr. Assoc. Adv. Science, Vol. 12, 1909, p. 173):
A. *Ordovician* (?): Diabase, diabase porphyrite, diorite, granophyre, microgranite.
B. *Silurian:* Andesitic tuff.
C. *Lower Devonian* (?): Quartz porphyry, syenite porphyry, sölvsbergite, bostonite, alkaline trachyte, quartz keratophyre, granodiorite, dacite, quartz porphyrite, granite porphyry.
D. *Middle Devonian:* Diabase, diabase porphyrite, rhyolite, biotite andesite, augite andesite, hornblende andesite.
E. *Upper Devonian, or Lower Carboniferous:* Basalt, rhyolite, quartz porphyry.

F. *Lower Cenozoic:* Basalt, augite andesite.
G. *Middle Cenozoic:*
1. Sölvsbergite.
2. Alkaline trachyte.
3. Basalt with anorthoclase.
4. Olivine trachyte.
5. Olivine-anorthoclase trachyte.

6. Limburgite.
7. Basalt.

H. *Upper Cenozoic to Recent:* Basalt, olivine basalt, limburgite, haüynite-bearing dolerite.

East Moreton and Wide Bay Districts, Queensland (H. I. Jensen, Proc. Linn. Soc. New South Wales, 1906, Part 1, p. 166):

A. *Pre-Carboniferous:* Diabase, greenstone.
B. *Carboniferous-Permian:* Tonalite, quartz diorite, granite.

C. *Cretaceous* (?): Porphyrite, tonalite, monzonite, soda-andesite, quartz andesite.
D. *Eocene* (?): Trachyte, rhyolite, keratophyre, comendite.
E. *Late Eocene* (?): Dacite, andesite.
F. *Pliocene* (?): Basalt.

APPENDIX C

TABLE XXII.—LISTS OF DISTRICTS CHARACTERIZED BY MEMBERS OF THE SYENITE CLAN, WITH NOTES ON THE NATURE OF COUNTRY-ROCKS

(See page 395; many references to authors found in Rosenbusch's handbook.)

FIELD ASSOCIATIONS OF THE SYENITE CLAN

Region	Representatives of syenite clan and other alkaline clans	Sediments cut by eruptives[1]
	NORTH AMERICA	
QUEBEC.		
Mt. Shefford.	Pulaskite, nordmarkite, essexite, theralite, camptonite, bostonite, trachyte.	Paleozoic sh., cg., li., ss.
Mt. Johnson.	Pulaskite, essexite, camptonite, sölvsbergite (?).	Ditto.
Mt. Brome.	Nordmarkite, laurvikitic syenite, essexite.	Paleozoic sh. and li.
Mt. Orford.	Nordmarkite, monzonite, camptonite.	Ditto.
Grenville.	Hornblende syenite, quartz-syenite porphyry.	Pre-Cambrian li. and para-gneisses.
Mt. Rigaud.	Hornblende syenite; alkaline quartz porphyry.	?
Ottawa County.	Syenite orthogneiss.	Pre-Cambrian li., and quartzite.
Keekeek and Kewagama lakes.	Syenite.	Pre-Cambrian basic schists.
Metagami Lake.	Syenite porphyry.	Keewatin greenstones; Huronian sl., cg., arkose.
NOVA SCOTIA.		
Arisaig-Antigonish district.	Monzonite.	Cambrian sl., grits, and graywackes.

[1]*Abbreviations:* Arg.—argillite; cg.—conglomerate; li.—limestone; sh.—shale; sl.—slate; ss.—sandstone.

TABLE XXII.—FIELD ASSOCIATIONS OF THE SYENITE CLAN.—*Continued*

Region	Representatives of syenite clan and other alkaline clans	Sediments cut by eruptives
ONTARIO.		
Larder Lake Dist.	Syenite.	Keewatin green schists, sl., and dolomite.
Abitibi Lake.	Hornblende-albite syenite, quartz-albite syenite.	Keewatin green schists; sl., dolomite.
Monmouth Township.	Alkaline syenite, alk. granite, nephelite syenite, monmouthite.	Grenville li.; schists.
Glamorgan Tp.	Albite syenite, nephelite syenite.	Ditto.
Harcourt Tp.	Corundum syenite, nephelite syenite.	Ditto
Methuen Tp.	Ditto.	Amphibolite, li., gneiss.
Faraday Tp.	Alkaline syenite, nephelite syenite.	?
Monteagle Tp.	Ditto.	Li.
Raglan Tp.	Alkaline syenite, craigmontite, nephelite syenite, corundum syenite.	Ditto.
Nipissing-Timiskaming Dist.	Syenite orthogneiss.	Huronian sl. and graywacke. (Grenville li.?).
Pigeon Lake (Montreal river).	Hornblende syenite.	?
Lutterworth Tp.	Corundum syenite.	Grenville li., etc.
Port Coldwell.	Hornblende syenite, nephelite syenite, quartz syenite, essexite, camptonite, alkaline granite.	Keewatin chlorite schist and greenstone; Laurentian schists.
Rainy Lake.	Hornblende and mica syenite.	Keewatin green schist; cg., sl., etc.
Sturgeon Lake.	Hornblende syenite.	Ditto.

TABLE XXII.—FIELD ASSOCIATIONS OF THE SYENITE CLAN.—*Continued*

Region	Representatives of syenite clan and other alkaline clans	Sediments cut by eruptives
Gunflint Dist.	Hornblende syenite.	Keewatin green schist; cg., sl., etc.
ALBERTA.		
Blairmore.	Analcite trachyte.	Paleozoic li., sh., etc.
BRITISH COLUMBIA		
Camp Hedley.	Monzonite, keratophyre.	Paleozoic arg., li., etc.
Roche River.	Syenite.	Ditto.
Tulameen Dist.	Augite syenite.	Triassic arg., li., and basic volcanics; probably-Paleozoic li. and arg.
Edwards Creek.	Porphyritic syenite.	Paleozoic li., sh., chert, and greenstone.
Bonaparte Lake.	Augite syenite.	?
Franklin Camp.	Monzonite, syenite, pulaskite porphyry.	Paleozoic li., arg., and greenstone.
Phoenix Dist.	Syenite, syenite porphyry, trachyte.	Ditto.
Nelson Dist.	Monzonite.	Ditto.
Rossland Dist.	Monzonite, latites, missourite.	Paleozoic li., arg., etc.
Salmon River.	Monzonite.	Ditto.
Christina Lake.	Pulaskite (Coryell batholith).	Ditto.
Kettle River (Midway).	Pulaskite porphyry, alkaline trachyte, rhomb-porphyry, shackanite.	Ditto.
Skagit Range.	Monzonite.	Ditto.
Siwash Creek District.	Syenite porphyry.	Paleozoic (?) sl., schist, li.
Shuswap Lake (Salmon Arm).	Hornblende syenite.	Pre-Cambrian li., phyllites, etc.

TABLE XXII.—FIELD ASSOCIATIONS OF THE SYENITE CLAN.—*Continued*

Region	Representatives of syenite clan and other alkaline clans	Sediments cut by eruptives
ALASKA.		
Naknek Lake.	Syenite.	Mesozoic sh., li., and chert.
Copper Mt. and Moira Sound.	Syenite, trachyte.	Paleozoic (?) sh., li., and greenstone.
Kluane River.	Syenite.	Paleozoic sl., li.
Treadwell Mine.	Sodium syenite.	Thick sl.
Chichagof Cove.	Alkali-syenite porphyry, latite.	Cenozoic sh., ss., li., grit.
Kichatna Valley.	Olivine monzonite.	Jurassic sl.
Rampart Region.	Monzonite.	Paleozoic arg., li., ss.
Lynx Mt.	Monzonite.	Paleozoic arg., li., ss.
Glenn Creek.	Monzonite.	Paleozoic arg., li., ss.
Copper River.	Monzonite.	Probably cuts arg. and li., etc., of Valdez and Paleozoic series.
Yentna River.	Hornblende syenite.	?
Swentna River.	Quartz syenite.	Thick sh.
Kasaan Peninsula.	Syenite.	Paleozoic ss., cg., li., and greenstone.
Matanuska Valley.	Trachyte.	Cenozoic and Mesozoic sh., ss., cg., li., and basic igneous rocks.
YUKON.		
Wheaton River Dist.	Syenite, syenite porphyry, trachyte.	Paleozoic (?) li., green schists and quartzites; also probably-Mesozoic arg., ss., cg.
Lake Labarge.	Syenite porphyry.	Carboniferous li.; also ss., sh., tuffs.
White Horse Copper Belt.	Syenite porphyry, bostonite.	Paleozoic li.

TABLE XXII.—FIELD ASSOCIATIONS OF THE SYENITE CLAN.—*Continued*

Region	Representatives of syenite clan and other alkaline clans	Sediments cut by eruptives
WASHINGTON.		
Myers Creek Dist.	Hornblende syenite.	Paleozoic sl., li., greenstone and quartzite.
IDAHO.		
Vermilion Creek.	Syenite.	Pre-Cambrian sh., ss., possibly calcareous beds.
Upper St. Joe River.	Monzonite, camptonite.	Pre-Cambrian sh., li., ss.
Coeur D'Alene Dist.	Monzonite, monzonite porphyry, syenite.	Pre-Cambrian sh., li., ss.
MONTANA.		
Elkhorn Dist.	Syenite, shonkinite, bostonite.	Cambrian and older arg., li., and quartzite.
Helena Dist.	Latite, monzonite.	Paleozoic and Beltian arg., li., quartzite.
Three Forks Quadrangle.	Syenite.	Pre-Cambrian li., ss., cg.
Bozeman.	Corundum syenite.	?
Sweet Grass Hills.	Quartz syenite porphyry, minette.	Cretaceous sh., etc.
Castle Mts.	Syenite porphyry, acmite trachyte, theralite, monchiquite.	Paleozoic and older sh., li., ss.
Little Belt Mts.	Syenite, monzonite, shonkinite, trachyte, syenite porphyry, etc.	Paleozoic and older sh., li., ss.
Crazy Mts.	Acmite trachyte, theralite.	Paleozoic and older sh., li., ss.
Highwood Mts.	Syenite, monzonite, shonkinite, etc.	Paleozoic and older sh., li., ss.

TABLE XXII.—FIELD ASSOCIATIONS OF THE SYENITE CLAN.—*Continued*

Region	Representatives of syenite clan and other alkaline clans	Sediments cut by eruptives
Judith Mts.	Syenite, tinguaite, etc.	Paleozoic and older sh., li., ss.
Bearpaw Mts.	Mica trachyte, monzonite, shonkinite, augite syenite, nephelite basalt, leucite tinguaite, leucite basalt.	Paleozoic and Mesozoic li., sh., ss., etc.
Bannock, Beaverhead Co.	Syenite.	"Paleozoic sediments."
WYOMING.		
Crandall Quadrangle.	Monzonite, syenite, shoshonite.	?
Sundance Quadrangle.	Monzonite porphyry, syenite porphyry, nephelite syenite, bostonite, alk. lamprophyres.	Paleozoic li., sh., etc.
Absaroka Quadrangle.	Monzonite, syenite, quartz syenite.	Paleozoic li., sh., and quartzite.
Laramie Mts.	Syenite.	Pre-Cambrian mica schist, hornblende schist, and perhaps li.
Aladdin Quadrangle.	Syenite porphyry, phonolite, pseudo-leucite porphyry, etc.	Paleozoic li., ss., etc.; Pre-Cambrian schists.
COLORADO.		
Rico Dist.	Monzonite, monzonite porphyry.	Paleozoic and Mesozoic sh., li., ss.
La Plata Quad.	Monzonite, monzonite porph., augite syenite, syenite porph.	Paleozoic and Mesozoic sh., li., ss.
Telluride Quad.	Monzonite.	Paleozoic and Mesozoic sh., li., ss.
Spanish Peaks.	Monzonite porphyry.	Paleozoic and Mesozoic sh., li., ss.
North Peak.	Trachyte.	Paleozoic and Mesozoic sh., li., ss.
Cripple Creek.	Olivine syenite, syenite, phonolite, trachydolerite, etc.	? (Pre-Cambrian granite!)

TABLE XXII.—FIELD ASSOCIATIONS OF THE SYENITE CLAN.—*Continued*

Region	Representatives of syenite clan and other alkaline clans	Sediments cut by eruptives
Georgetown Quad.	Syenite porphyry, latite, bostonite, etc.	Pre-Cambrian li.
Evergreen Mine, Gilpin Co.	Monzonite.	Metasedimentary biotite schists, with calcareous phases.
Silver Cliff and Rosita Hills.	Syenite, trachyte.	(Pre-Cambrian granite-gneiss!).
Engineer Mt. Quad.	Monzonite, monzonite porph., monchiquite, camptonite.	Paleozoic sh., li., ss.
Two Buttes.	Syenitic lamprohyres.	Triassic sediments (and ?).
Leadville.	Trachyte.	Li., granite.
Denver Basin.	Augite syenite.	(Pre-Cambrian gneiss!).
Elkhead Mts.	Trachyte, nephelite basalt.	Cretaceous?
Durango Quad.	Monzonite porphyry.	Permian (?) calcareous argillite, ss., cg.
Sangre de Cristo Range.	Syenite orthogneiss.	?
Breckenridge Dist.	Monzonite porphyry, quartz-monzonite porphyry.	Pre-Cambrian mica schists; Mesozoic sh., li., cg., ss.
Silverton Quad.	Ditto, with latite.	Pre-Cambrian schists and sl.; Paleozoic sh., li., ss., quartzite.
Ouray Quad.	Latite, quartz-monzonite porphyry.	Paleozoic sh., li., ss., etc.
Twin Butte.	Syenite porphyry.	Mesozoic sh., ss.
Grayback Dist., Costilla Co.	Monzonite.	Paleozoic sediments.
California Dist., La Plata Co.	Monzonite porphyry.	"Red Beds."
East Mancos Dist. Montezuma Co.	Monzonite.	"Red Beds."

TABLE XXII.—FIELD ASSOCIATIONS OF THE SYENITE CLAN.—*Continued*

Region	Representatives of syenite clan and other alkaline clans	Sediments cut by eruptives
Tarryall Dist., Park Co.	Monzonite.	Paleozoic and Mesozoic sediments.
Monarch and Tomichi Dist., Chaffee Co.	Monzonite, quartz monzonite, latite.	Paleozoic li., sh., quartzite.
UTAH.		
Tintic Dist.	Monzonite, monzonite porph., latite.	Paleozoic li., chert, quartzite.
Bingham Dist.	Monzonite, monzonite porph.	Paleozoic li., chert, quartzite.
High Plateaus.	Many trachyte masses.	Paleozoic li., sh., quartzite, etc.
Cactus Mine (San Francisco Mts.)	Monzonite.	Li. and quartzite, probably Paleozoic.
Downtown Dist.	Monzonite porphyry., quartz monzonite porphyry	Paleozoic li. and quartzite.
Big Cottonwood Canyon.	Syenite porphyry.	Paleozoic li., sh., etc.
Twin Peak.	Trachyte.	Cambrian sl.
Western Uinta Range.	Trachyte.	Paleozoic li., quartzite; also probably Mesozoic li., ss.
City Creek and Easy Canyon Cr.	Trachyte.	Paleozoic and Mesozoic li., sh., quartzite.
Fountain Head Hills (Utah?).	Trachyte.	Paleozoic li., and quartzite.
Oquirrh Range.	Trachyte.	Carboniferous li.
Stansbury Range.	Trachyte.	"Paleozoic strata."
Cedar Range.	Trachyte.	?
Thomas Range.	Trachyte.	Paleozoic li.
Picacho Range.	Trachyte.	?

TABLE XXII.—FIELD ASSOCIATIONS OF THE SYENITE CLAN.—*Continued*

Region	Representatives of syenite clan and other alkaline clans	Sediments cut by eruptives
Marysvale, Tushar Range.	Monzonite, quartz monzonite, quartz latite.	Mesozoic and Paleozoic li. and quartzite.
Beaver Lake Dist.	Monzonitc.	"Paleozoic sediments."
North Star Dist.	Monzonite.	"Paleozoic sediments."
Preuss Dist.	Monzonite.	"Paleozoic sediments."
Rocky Dist.	Monzonite.	"Paleozoic sediments."
Frisco Dist.	Monzonite.	"Paleozoic sediments."
Miner's Basin, Grand Co.	Monzonite porphyry.	?
Ophir Dist., Tooele Dist.	Monzonite.	Paleozoic sediments.
NEVADA.		
Cactus Range.	Latite.	Paleozoic li., cg., and quartzite.
Stonewall Mt.	Monzonite porphyry, quartz syenite.	Thick Cambrian li., etc.
Goldfield Hills.	Latite, quartz latite.	Probably cuts Cambrian li. and sh.
Southern Klondike Hills.	Quartz latite.	Cambrian li. and sh.
Silver Peak Range.	Latite, monzonite.	Cambrian li. and sh.
Kawich Range.	Monzonite porphyry.	Paleozoic li., sh., ss.
Belted Range.	Monzonite.	Probably cuts Cambrian li. and sh.
Pahute Range.	Monzonite.	Probably cuts Cambrian li. and sh.
Yucca Mt.	Latite.	Paleozoic li. and quartzite.
Amargosa Range.	Latite.	Paleozoic li. and quartzite.

TABLE XXII.—FIELD ASSOCIATIONS OF THE SYENITE CLAN.—*Continued*

Region	Representatives of syenite clan and other alkaline clans	Sediments cut by eruptives.
Panamint Range.	Soda syenite, quartz monzonite	Paleozoic li. and quartzite.
Cortez Range.	Syenite, syenite porph., trachyte.	Paleozoic li. and quartzite.
Black Butte and Eugene Mts.	Syenite.	Paleozoic sl., li., ss.
Montezuma Range.	Syenite.	Jurassic sl., li., ss.
Winnemuca Peak.	Syenite.	Jurassic (?) sl., li., ss.
Pyramid Lake.	Trachyte.	?
Virginia Range.	Trachyte.	?
Seetoya Mts.	Trachyte.	Paleozoic li. and quartzite.
Pinon Range.	Trachyte.	Paleozoic li. and quartzite.
East Humboldt Range.	Trachyte.	Paleozoic li. and quartzite.
Wah-weah Range.	Haüynite-bearing trachyte.	Paleozoic sediments.
River Range.	Trachyte.	Paleozoic li. and quartzite.
Shoshone Range.	Trachyte.	Paleozoic li. and quartzite.
Kawsoh Range.	Trachyte.	?
Pahroc Range.	Trachyte.	?
Robinson Mining Camp.	Monzonite, monzonite porphyry, minette.	Paleozoic li. and sh.
Contact Mining.	Syenite.	Paleozoic li. and sh.
Bare Mt. Dist.	Monzonite porphyry.	Paleozoic sediments.
Ward Dist.	Monzonite porphyry.	Paleozoic sediments.
White Pine Dist.	Monzonite.	Paleozoic sediments.

TABLE XXII.—FIELD ASSOCIATIONS OF THE SYENITE CLAN.—*Continued*

Region	Representatives of syenite clan and other alkaline clans	Sediments cut by eruptives
CALIFORNIA.		
Big Trees Quad.	Syenite, latite.	Paleozoic arg., li., quartzite.
Nevada City Quad.	Augite syenite, monzonite.	Paleozoic arg., li., quartzite.
Sonora Quad.	Soda syenite.	Mesozoic and Paleozoic arg., li., and ss.
Spanish Peaks (Bidwell Bar Quad.)	Soda syenite, plumasite.	?
Downieville Quad.	Syenite porphyry.	Clay sl.
Inyo County.	Hornblende syenite.	Silurian li.
Darwin Dist. (Inyo Co.)	Monzonite.	Paleozoic sediments.
Goldbelt Dist. (Inyo Co.)	Monzonite.	Paleozoic sediments.
Skidoo Dist.	Monzonite, syenite.	?
Virginia Dale Dist.	Syenite.	"Sediments"
Mother Lode Dist.	Latite.	Paleozoic li., sl.
Eagle Mts.	Monzonite, syenite, granodiorite, quartz monzonite.	Thick dolomite and quartzite.
ARIZONA.		
Bradshaw Mts.	Monzonite porphyry, trachydolerite.	Phyllite, mica schists, hornblende schist, li., cg., quartzite.
Bisbee Quad.	Monzonite porphyry.	Paleozoic li., quartzite, etc.
Globe Quad.	Monzonite (quartz monzonite).	Paleozoic sediments.
Sierra Escudillo.	Trachyte.	?
Sierra Caluiro.	Trachyte.	?
Asbestos Canyon.	Hornblende syenite.	Unkar li., sh.; Vishnu schists.

TABLE XXII.—FIELD ASSOCIATIONS OF THE SYENITE CLAN.—*Continued*

Region	Representatives of syenite clans and other alkaline clans	Sediments cut by eruptives
Dripping Springs Dist.	Monzonite porphyry.	Paleozoic sediments.
Riverside Dist.	Monzonite porphyry.	Paleozoic sediments.
Silver King Dist.	Syenite.	Paleozoic sediments; pre-Cambrian schists.
Castle Dome Dist.	Monzonite porphyry.	Pre-Cambrian schist.
Turquoise Dist. (Dragoon Mts.)	Monzonite porphyry.	Paleozoic sh., li., quartzite.
NEW MEXICO.		
Walsenburg Quad.	Monzonite porphyry.	Paleozoic li. and other sediments.
Cerrillos Hills.	Monzonite porphyry.	Mesozoic arg. and ss. (also Paleozoic sediments?)
Deming.	Monzonite porphyry.	Paleozoic li., sh., ss.
Sierra Luera.	Trachyte.	?
Cook's Peak.	Syenite.	Carboniferous li.
Burro Mts.	Latite, trachyte, quartz monzonite.	Probably cut Cretaceous sh. and li.
Pinos Altos.	Monzonite, syenite, trachyte, granodiorite.	?
Cimarroncito Dist.	Monzonite.	Carboniferous and Cretaceous sediments.
Moreno Dist.	Monzonite porphyry.	Paleozoic and Cretaceous sediments.
Ute Creek Dist.	Monzonite.	Paleozoic and Cretaceous sediments.
Black Mt. Dist.	Monzonite.	Paleozoic sediments.
Nogal Dist.	Monzonite porphyry.	?

TABLE XXII.—FIELD ASSOCIATIONS OF THE SYENITE CLAN.—*Continued*

Region	Representatives of syenite clan and other alkaline clans	Sediments cut by eruptives
Whiteoaks Dist.	Monzonite.	Cretaceous sediments.
Tres Hermanas Dist.	Quartz syenite.	Paleozoic sediments.
Jarilla Dist.	Monzonite porphyry.	Paleozoic sediments.
Cochiti Dist.	Monzonite.	?
Hillsboro Dist.	Monzonite.	Paleozoic sediments.
Tierra Blanca Dist.	Monzonite.	Paleozoic sediments.
Jones Camp Dist.	Monzonite.	Paleozoic li.
Magdalena Dist.	Monzonite.	Paleozoic sediments.
Red River Dist.	Monzonite porphyry.	Pre-Cambrian schist and granite.
TEXAS.		
Brewster County.	Trachyte, phonolite.	Thick Cretaceous li. and sh.
Franklin Mts.	Monzonite porphyry.	Pre-Cambrian sl., very thick Paleozoic li.
Apache Mts.	Syenites, nephelite syenite, phonolite, bostonite, tinguaite, paisanite.	Paleozoic and Mesozoic li.
El Paso Quad.	Syenite porphyry.	Paleozoic li., ss.
ARKANSAS.		
Magnet Cove.	Shonkinite, nephelite syenite, etc.	Paleozoic li.
VIRGINIA.		
Luray Dist.	Syenite.	?
"Blue Ridge Region."	Hypersthene akerite.	?
"Southwest Virginia."	Hornblende syenite.	Basic schists and diorite.

TABLE XXII.—FIELD ASSOCIATIONS OF THE SYENITE CLAN.—*Continued*

Region	Representatives of syenite clan and other alkaline clans	Sediments cut by eruptives
WISCONSIN.		
North Central Wis.	Mica syenite, quartz syenite, syenite.	Pre-Cambrian sl., graywacke, calcareous arg., quartzite.
MICHIGAN.		
Penokee Dist.	Syenite.	Mica schists and gneisses.
Marquette Dist.	Hornblende syenite.	Thick pre-Cambrian sl. and greenstone.
MINNESOTA.		
Kekequabic Lake.	Nordmarkite.	Pre-Cambrian arg., graywacke, grit, green schists.
Mesabi Range.	Soda syenite.	Pre-Cambrian sl.
Basswood Lake.	Syenite.	Sl., mica schist, quartzite.
Sauk Center.	Syenite.	Mica schists.
White Iron Lake.	Syenite.	Arg., mica schist, quartzite.
Other localities.	Trachyte.	Sl.
Red Rock areas.	Syenitic phases.	Animikie sl.
NEW YORK.		
Thousand Islands.	Various syenites.	Grenville li., quartzite, etc.
Little Falls Quad.	Syenite.	Grenville li., quartzite, etc.
Elizabethtown-Port Henry Quad.	Syenite.	Grenville li., quartzite, etc.
Paradox Lake Quad.	Syenite.	Grenville li., quartzite, etc.
Long Lake Quad.	Syenite.	Grenville li., quartzite, etc.
North Creek Quad.	Syenite.	Grenville li., quartzite, etc.
Lyon Mt.	Trachyte, bostonite.	(Laurentian gneiss!).

TABLE XXII.—FIELD ASSOCIATIONS OF THE SYENITE CLAN.—*Continued*

Region	Representatives of syenite clan and other alkaline clans	Sediments cut by eruptives
Loon Lake.	Augite syenite.	Grenville li., quartzite, gneisses.
Peekskill.	Syenite, monzonite.	Mica and graphitic schists; (li.?).
Cortlandt Dist.	Syenite, trachyte, sodalite syenite.	Basic schists, li., quartzite, serpentine.
Brewster Dist.	Syenite.	Mica schist, li., paragneisses.
VERMONT.		
Mt. Ascutney.	Nordmarkite, pulaskite, monzonite, etc.	Calciferous mica schist, li.
Cuttingsville.	Syenite, essexite, etc.	Schists, li.
NEW HAMPSHIRE.		
Red Hill.	Umptekite, foyaite, paisanite, bostonite, camptonite.	?
Jackson.	Augite syenite.	?
Columbia.	Hornblende syenite.	?
Sandwich.	Hornblende syenite.	?
Stark.	Hornblende syenite.	?
Albany.	Hornblende syenite.	?
Belknap Mts.	Syenite, essexite, camptonite.	Basic mica schists (Montalban and Rockingham).
Tripyramid Mt.	Monzonite, syenite.	?
MAINE.		
AroostookCounty.	Syenite, trachyte, teschenite.	Paleozoic li., sh., ss.
Penobstock Bay Quadrangle.	Syenite, trachyte.	Sl., li., quartzite; pre-Cambrian schist.

TABLE XXII.—FIELD ASSOCIATIONS OF THE SYENITE CLAN.—*Continued*

Region	Representatives of syenite clan and other alkaline clans	Sediments cut by eruptives
MASSACHUSETTS.		
Neponset Valley.	Trachyte porphyry.	Cambrian arg.
Essex County.	Nordmarkite, akerite, etc.	Paleozoic li., arg., quartzite, etc.
CONNECTICUT.		
Fair Haven.	Keratophyre.	Triassic ss.
MEXICO.		
Altar Dist.	Syenite.	?
Cerro de Muleros.	Syenite porphyry.	Cretaceous li., ss., and marl.
Ferreria San Esteban.	Trachyte.	?
Santa Catarina.	Trachyte.	?
Sierra de las Cruces.	Trachyte.	?
Mazapil Valley.	Syenite.	Jurassic and Cretaceous ss., li., sh.
Cananea Dist.	Syenite, syenite porphyry.	Thick Tertiary li. and volcanics.
San Jose Dist.	Syenite, nephelite syenite, camptonite, tinguaite.	Thick Cretaceous li.
	SOUTH AMERICA	
Colombia.	Syenite, syenite porphyry.	Phyllites, amphibolites, quartzites.
Rio Magdalena (Colombia).	Latite, quartz syenite, quartz monzonite.	Cretaceous and older "Schichten."
Sao Paulo, Brazil.	Augite syenite, laurvikite, foyaite, etc.	Paleozoic li., sl. (also pre-Cambrian basic schist and li.?)
Matto Grosso, Brazil.	Augite syenite.	Paleozoic li., sl., ss.

TABLE XXII.—FIELD ASSOCIATIONS OF THE SYENITE CLAN.—*Continued*

Region	Representatives of syenite clan and other alkaline clans	Sediment cut by eruptives
Madeira River, Brazil.	Augite syenite.	?
Cabo Frio, Brazil.	Pulaskite.	?
Ceara, Brazil.	Hornblende syenite.	Pre-Cambrian paragneisses and li.
Sao Thomé, Brazil.	Trachyte.	?
Rio Payne.	Akerite.	? (probably cuts Mesozoic sediments).
Aconcagua.	Trachyte.	Mesozoic li., etc.
French Guiana.	Syenite.	? (probably cuts basic schists and li. adjacent).
Cerro Balmaceda, Patagonia.	Monzonites, nordmarkite, pyroxene syenite.	Mesozoic sl., li., marl.
British Guiana.	Syenite.	?
	EUROPE	
GREAT BRITAIN.		
Island of Skye.	Trachyte, trachyandesite, syenite, alkaline granite.	Mesozoic and Paleozoic sh., li.
Kiloran Bay, Scotland.	Syenite, kentallenite, monchiquite.	?
Argyllshire.	Kentallenite.	"Highland schists."
Loch Borolan.	Nordmarkite, borolanite, nephelite syenite, etc.	Cambrian li. and quartzite; Torridonian ss., Moine schists.
Colonsay and Oronsay.	Quartz syenite, kentallenite, monchiquite, etc.	Lower Torridonian li., phyllite, ss., grit, cg., etc.
Pembrokeshire.	Trachytes, keratophyre, etc.	Cambrian sl. ("Dimetian" li.?)

TABLE XXII.—FIELD ASSOCIATIONS OF THE SYENITE CLAN.—*Continued*

Region	Representatives of syenite clan and other alkaline clans	Sediments cut by eruptives
FRANCE.		
Mont Dore.	Trachyte, etc.	Pre-Cambrian mica schists, phyllite; Tertiary li.
Savoy.	Orthophyre.	Mica schists, amphibolite, ss., cg.
Isère.	Syenite.	?
Mayenne.	Syenite.	?
Velay.	Trachyte, phonolite.	Tertiary marls, li.
Morvan.	Trachyte, syenite.	Devonian sl., ss., li. and pre-Devonian schists.
La Sioule Valley (Puy-de-Dome Dist.).	Trachyte.	Cambrian-Devonian sl.
SPAIN, PORTUGAL.		
Fortuna, Spain.	Trachyte.	Cretaceous li., Tertiary marls.
Serra de Monchique.	Pulaskite, etc.	Paleozoic li.
ITALY.		
Biella, Italy.	Syenite.	Mica schists, gneiss.
Euganean Hills.	Trachyte.	Eocene marls.
Ischia.	Trachyte.	Tertiary and Mesozoic clays, marls, li.
Many localities elsewhere in Italy	Trachyte, etc.	Tertiary and Mesozoic clays, marls, li.
SWITZERLAND.		
Aar Massif, Switzerland.	Syenite.	Pre-Carboniferous "sediments.

TABLE XXII.—FIELD ASSOCIATIONS OF THE SYENITE CLAN.—*Continued*

Region	Representatives of syenite clan and other alkaline clans	Sediment cut by eruptives
BALKANS.		
Montenegro.	Trachyte.	Triassic li., older sediments.
Dobrogea.	Nordmarkite, paisanite, etc.	Paleozoic sh., li., ss., etc.
AUSTRIAN EMPIRE.		
Monzoni.	Monzonite, etc.	Triassic li.; ss., etc.
Predazzo.	Monzonite, shonkinite, nephelite syenite, etc.	Triassic li., older sediments.
Duppau Hills, Bohemia.	Augite syenite, phonolite, etc.	Tertiary marls and calcareous tuffs.
Mittelgebirge, Bohemia.	Trachyte, phonolite, etc.	Mesozoic and Paleozoic li., marl, etc.; pre-Cambrian mica and hornblende schists.
Vihorlat-Gutin Mts.	Trachyte.	Ss., sl., li.
Bulza Mts.	Trachyte.	?
Brunn.	Syenite.	Limestone.
Blansko, Moravia.	Syenite.	?
Gleichenberg	Trachyte, nephelinite, etc.	?
Holbak, Siebenbürgen.	Aegerite trachyte.	"Crystalline schists."
Bukowina.	Quartz keratophyre.	Sl., li., ss., marly sl.
GERMANY.		
Lower Silesia.	Syenite.	Mica schist, li.
Plauen Grund.	Syenite.	?
Erzgebirge, Saxony.	Syenite porphyry.	Mica schist, li., gneiss, graywacke.
Dohlen Coal Dist.	Syenite.	Silurian phyllite.
Ober Lausitz.	Syenite porphyry.	Paleozoic clay sl.
Westerwald.	Trachyte, trachyandesite.	Devonian sl., quartzite, etc.

TABLE XXII.—FIELD ASSOCIATIONS OF THE SYENITE CLAN.—*Continued*

Region	Representatives of syenite clan and other alkaline clans	Sediments cut by eruptives
Rothschönberg.	Mica syenite.	Phyllites.
Harz.	Keratophyre.	Probably Paleozoic sl., li., graywacke (?).
Katzenbuckel.	Shonkinite, theralite, etc.	Mesozoic li. and dolomite.
Northern Odenwald.	Trachytes.	?
Rhön.	Trachyte, phonolite, etc.	Mesozoic li. and Paleozoic calcareous sediments.
Vogelsberg.	Trachyte, phonolite, etc.	Mesozoic li. and Paleozoic calcareous sediments.
Siebengebirge.	Trachyte, essexite, etc.	Devonian calcareous graywacke and older sediments.
Laacher See.	Sanidinite, etc.	Devonian calcareous graywacke and older sediments.
Eifel.	Trachyte, phonolite, etc.	Devonian arg., etc.
RUSSIA.		
Magnetberg, Urals.	Syenite, syenite porphyry, keratophyre.	Paleozoic li.
Zalas, near Cracow.	Syenite porphyry.	Mesozoic li.; Carboniferous and older sediments.
Miask, Russia.	Corundum syenite, nephelite syenite, etc.	Crystalline li.
Azof, Russia.	Orthophyre, grorudite, etc.	Paleozoic li. ?
Piatigorsk (northern Caucasus).	Trachyte, alkaline liparite.	Eocene and Mesozoic sediments.
Ahvenaara, Finland	Syenite, essexite, etc.	?
Kola peninsula.	Umptekite, nephelite syenite, etc.	Marly clay slate, etc.

TABLE XXII. FIELD ASSOCIATIONS OF THE SYENITE CLAN.—*Continued*

Region	Representatives of syenite clan and other alkaline clans	Sediments cut by eruptives
SWEDEN.		
Northern Småland.	Orthophyre, catapleiite syenite	? (Granite, effusive quartz porphyry).
Gellivåre Dist.	Syenite, quartz syenite, alkaline granite.	Mica schists, amphibolite.
Ragunda Dist.	Nordmarkite.	Schists.
Ekströmsberg Dist.	Soda syenite, keratophyre.	Chlorite schist, li., quartzite, etc.
Laukkujärvi.	Syenite granulite.	Li. and greenstone.
Svoppavaara.	Alkaline syenites.	Ditto.
Mertainen.	Syenite.	?
Painirova.	Syenite porphyry.	?
Kiruna Dist.	Ditto.	Greenstone; also probably li. and other basic sediments.
Torne Träsk, Lappland.	Syenite.	Pre-Cambrian green schists and dolomite.
NORWAY.		
Bergen, Norway.	Monzonite, soda syenite, mangerite.	Pre-Cambrian mica schists; Silurian "sediments."
Christiania Region.	Monzonite, nordmarkite, pulaskite, etc.	Paleozoic li. and argillite.
	ASIA	
Tsang and Ü provinces, Tibet.	Syenite.	Paleozoic and Mesozoic sl. and li.
Western Shantung, China.	Syenite porphyry, quartz syenite porphyry.	Paleozoic sh., ss., li.
Korea (Park-tsch'-hou).	Syenite porphyry.	Phyllite.

TABLE XXII.—FIELD ASSOCIATIONS OF THE SYENITE CLAN.—*Continued*

Region	Representatives of syenite clan and other alkaline clans	Sediments cut by eruptives
Urtini Highland (Lena River).	Monzonite, syenite.	Schists, sl., thick li.
Yenisei.	Monzonite, umptekite, etc.	Sl., dolomite, thick li., phyllite, mica schist.
Mugodjaren Mts., Siberia.	Syenite.	Paleozoic sediments, including li.
Wyja-Teich (Ural).	Syenite-diorite.	?
Nijni-Tagilsk.	Syenite.	Li., sl., tuffs.
Blagodat, Ural.	Ditto.	Thick Devonian li., etc.
Vizagatapatam, India.	Charnockite, syenite.	?
Madras, India.	Augite syenite, corundum syenite, nephelite syenite.	?
Coimbatore Dist., India.	Corundum syenite.	"Crystalline schists."
Kalahandi.	Charnockite.	Pre-Cambrian li.
Ishan Peninsula, Arabia.	Alkaline trachyte.	?
Palandokan Plateau, Armenia.	Trachyte.	Probably cuts Mesozoic li. adjacent.
Demavend Volcano, Persia.	Trachyte.	Paleozoic and Mesozoic li. and ss.
Kadi-Kale, Smyrna.	Syenite.	Phyllite, cg., li. (?).
Kimituria Mine.	Trachyte.	Probably cuts li., etc.
Develikoi.	Ditto.	Phyllites, cg. and li. (?).
Sary-Boulak Gorge, Turkestan.	Syenite.	Li. and sl.
Borlo River, Turkestan.	Ditto.	Li.

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TABLE XXII.—FIELD ASSOCIATIONS OF THE SYENITE CLAN.—*Continued*

Region	Representatives of syenite clan and other alkaline clans	Sediments cut by eruptives
Kirai-guir River, Turkestan.	Ditto.	Li.
	AFRICA	
Abyssinian Plateau.	Trachyte, microsyenite.	Li., ss., phyllite, gneiss.
Great Rift Valley.	Trachyte, phonolite, etc.	?
Aïr, Central Africa.	Trachyte, phonolite.	Silurian li.
Socotra.	Syenite porphyry.	Amphibolite, gneiss.
Adamana, Kamerun.	Trachyte, phonolite, nephelite syenite.	Phyllite, green schist, marls, li., amphibolite, gneiss.
Cape Verde Peninsula.	Trachyte.	?
Fontaine du Génie, Algeria.	Monzonite.	?
Doornberg, Cape Colony.	Syenite.	Sh., ss., li., andesitic lavas.
Potchefstroom Dist.	Syenite, nephelite syenite.	Dolomite, ss., thick sl., quartzite.
Bushveldt.	Monzonite, nephelite syenite, bostonite, camptonite, monchiquite.	Sl., dolomite, quartzite.
Los Islands.	Pulaskite, monzonite, essexite, shonkinite, nephelite syenite, etc.	?
	AUSTRALIA	
NEW SOUTH WALES		
Warrumbungle Mts.	Trachyte, phonolite, etc.	Triassic calcareous sh., Paleozoic li. and sh.
Nandewar Mts.	Akerite, trachyte, nephelite syenite, etc.	Paleozoic li., sh., etc.
Canobolas Mts.	Trachyte.	Ditto.

TABLE XXII.—FIELD ASSOCIATIONS OF THE SYENITE CLAN.—*Continued*

Region	Representatives of syenite clan and other alkaline clans	Sediments cut by eruptives
Bowral.	Aegerite syenite.	Paleozoic li., sh., etc.
Mittagong.	Syenite, trachyte.	Ditto.
5 other districts.	Ditto.	Ditto.
QUEENSLAND		
5 districts.	Ditto.	?
VICTORIA.		
Mt. Macedon.	Trachytes.	Ordovician shales.
SOUTH AUSTRALIA		
Houghton.	Syenite.	Calcareous schist and li.
Aldgate.	Ditto.	Ditto.
Yankalilla.	Ditto.	?
	ISLANDS	
Port Cygnet, Tasmania.	Syenite, nephelite syenite, etc.	Paleozoic li., etc.
Dunedin, New Zealand.	Trachyte, foyaite, etc.	Tertiary li. and calcareous ss., etc.
Ross Archipelago.	Trachyte, kenyite, etc.	?
Possession Id.	Trachyte, phonolite.	?
Tahiti.	Trachyte.	?
Marquesas.	Monzonite, etc.	?
New Pomerania.	Monzonite.	?
Solomon Ids.	Trachyte.	?
Juan Fernandez.	Ditto.	?
Hawaii.	Ditto.	?

TABLE XXII.—FIELD ASSOCIATIONS OF THE SYENITE CLAN.—*Continued*

Region	Representatives of syenite clan and other alkaline clans	Sediments cut by eruptives
Oki Ids. (Japan).	Quartz syenite.	Tertiary sh., ss., etc.
Binangonan Peninsula, Philippines.	Trachyte.	Eocene li., etc.
Ulu Rawas, Sumatra.	Monzonite.	Sh., sl., li.
Madagascar (10 districts).	Monzonite, syenite, trachyte, etc.	Mesozoic arg., li., marl, etc.
Réunion.	Syenite, trachyte, etc.	?
Seychelles.	Syenite.	Clay slate.
Kerguelen.	Trachyte.	?
Ascension.	Alkaline trachyte.	?
Canary Ids.	Monzonite, etc	?
Madeira.	Trachyte.	?
Cape Verde Ids.	Syenite, foyaite, etc.	?
Azores.	Trachyte, etc.	Miocene li., etc.
Los Ids. (See p. 508.)	Pulaskite, monzonite, etc.	?
Samos.	Trachyte.	Li. and basic eruptives, etc.
Cyprus.	Trachyte.	Li., marls, basic eruptives.
Columbretes.	Ditto.	?
Lofoten Ids.	Monzonite, syenite.	Dolomite, gneiss.
Julianehaab, Greenland.	Nordmarkite, pulaskite, foyaite, etc.	(Granite and ss.!)

APPENDIX D

TABLE XXIII.—LIST OF DISTRICTS CHARACTERIZED BY ALKALINE ROCK-TYPES: WITH NOTES ON THE NATURE OF COUNTRY ROCKS

(See page 415 and also Appendix C)

Region	Alkaline eruptives	Carbonate rocks cut by alkaline eruptives[1]
	NORTH AMERICA	
QUEBEC.		
Mt. Brome.	Essexite, laurvikitic syenite, nordmarkite, etc.	Paleozoic li. and sh.
Mt. Johnson.	Essexite, camptonite, sölvsbergite, pulaskite.	Ditto.
Mt. Royal.	Essexite, nephelite syenite, bostonite, tinguaite, sölvsbergite, camptonite, fourchite, monchiquite, alnöite.	Ditto.
Mt. Shefford.	Essexite, theralite, bostonite, camptonite, pulaskite, etc.	Ditto.
Montarville.	Essexite.	Ditto.
Rougemont.	Essexite.	Ditto.
Mt. St. Hilaire (Beloeil).	Nephelite syenite, sodalite syenite, essexite, pulaskite.	Ditto.
Mt. Yamaska.	Essexite, akerite, yamaskite.	Ditto.
ONTARIO.		
Dungannon Tp.	Nephelite syenite.	Grenville li.
Faraday Tp.	Ditto.	Ditto.
Glamorgan Tp.	Ditto.	Ditto.
Harcourt Tp.	Ditto.	Ditto.
Methuen Tp.	Ditto.	Ditto.

[1] *Abbreviations:* Arg.—argillite; cg.—conglomerate; sh.—shale; sl.—slate; ss.—sandstone. Many references to authors found in Rosenbusch's handbook.

TABLE XXIII.—LIST OF DISTRICTS CHARACTERIZED BY ALKALINE ROCK-TYPES: WITH NOTES ON THE NATURE OF COUNTRY ROCK.—*Continued*

Region	Alkaline eruptives	Carbonate rocks cut by alkaline eruptives
Monteagle Tp.	Ditto.	Ditto.
Monmouth Tp.	Ditto.	Ditto.
Raglan Tp.	Ditto.	Ditto.
Wollaston Tp.	Ditto.	In diorite cutting Grenville li.
Pooh-bah Lake.	Malignite.	?
Port Coldwell.	Nephelite syenite, essexite, laurvikite, camptonite, etc.	? (Keewatin chlorite schists, etc.)
ALBERTA.		
Blairmore.	Analcite trachyte.	Paleozoic li., sh., etc.
BRITISH COLUMBIA.		
Ice River.	Nephelite syenite, ijolite, cancrinite syenite, urtite, tinguaite, etc.	Thick pre-Ordovician dolomites and li.
Rossland	Missourite, monzonite, latites.	Carboniferous li.
Kettle River.	Rhomb-porphyry, analcitic rhomb-porphyry, alkaline trachyte.	Paleozoic li., arg.
Camp Hedley.	Keratophyre, monzonite.	Ditto.
Kruger Mt.	Nephelite syenite, malignite.	Ditto.
MONTANA.		
Bearpaw Mts.	Leucite basalt, nephelite basalt, leucitite, tinguaite, trachytes, syenites.	Paleozoic and Mesozoic li. and dolomite.
Highwood Mts.	Leucite basalt, sodalite syenite, shonkinite, missourite, analcite basalt, syenites, etc.	Ditto.
Judith Mts.	Tinguaites, phonolites, syenite.	Ditto.

TABLE XXIII.—LIST OF DISTRICTS CHARACTERIZED BY ALKALINE ROCK-TYPES: WITH NOTES ON THE NATURE OF COUNTRY ROCKS.—*Continued*

Region	Alkaline eruptives	Carbonate rocks cut by alkaline eruptives
Little Belt Mts.	Analcite basalt, shonkinite, syenite, monzonite.	Ditto; also Beltian li.
Castle Mts.	Theralite, acmite trachyte.	Ditto.
Crazy Mts.	Ditto.	Ditto.
Elkhorn.	Shonkinite, bostonite, syenite.	Paleozoic argillaceous li.
WYOMING.		
Sundance Quadrangle.	Nephelite syenite, ijolite, leucite porphyry, bostonite, nephelinitc, camptonite, monzonite, etc.	Paleozoic li. and arg.
Aladdin Quad.	Ditto.	Ditto.
Absaroka Quad.	Leucitic syenite, etc.	Ditto.
Leucite Hills.	Wyomingite, orendite, madupite.	Paleozoic and Mesozoic li.
SOUTH DAKOTA.		
Black Hills.	Phonolite, grorudite, tinguaite.	Pre-Cambrian calcareous sediments; also (locally) Paleozoic and Mesozoic li.
COLORADO.		
Denver Basin.	Trachydolerite.	Mesozoic li.
Cripple Creek.	Nephelite syenite, phonolite, syenite, trachydolerite, etc.	(? Intruded into Pre-Cambrian granite!).
Georgetown.	Bostonite, latite, etc.	Li., calcareous sh. and ss.
Engineer Mt.	Monchiquite, camptonite, monzonite.	Paleozoic li., sh., ss.
Elkhead Mts.	Nephelite basalt, trachyte.	?

TABLE XXIII.—LIST OF DISTRICTS CHARACTERIZED BY ALKALINE ROCK-TYPES: WITH NOTES ON THE NATURE OF COUNTRY ROCKS.—*Continued*

Region	Alkaline eruptives	Carbonate rocks cut by alkaline eruptives
NEVADA.		
Bullfrog.	Leucite basalt.	Li.
NEW MEXICO.		
Las Vegas.	Analcitic camptonite.	Paleozoic li. and Mesozoic sediments.
CALIFORNIA.		
Point Sal.	Teschenite.	Tertiary li. and clays; Cretaceous shales.
San Luis Obispo County.	Ditto.	Ditto.
TEXAS.		
Brewster County.	Phonolite, trachyte.	Thick Cretaceous li. and sh.
Rio Grande Plain (Pilot Knob).	Nephelite basalt, melilite basalt, orthoclase basalt, phonolite, limburgite.	Cretaceous (and older?) li.
Apache Mts.	Nephelite syenite, phonolite, tinguaite, bostonite, paisanite, syenite.	Paleozoic and Mesozoic li. and marl.
Uvalde County.	Nephelite basalt and basanite, melilite basalt, phonolite, limburgite.	Mesozoic (and older?) li. and marls.
ARKANSAS.		
Magnet Cove.	Nephelite syenite, ijolite, shonkinite, jacupirangite, leucite porphyry, monchiquite, tinguaite.	Paleozoic magnesian li.
WISCONSIN.		
North-central part.	Nephelite syenite, syenites.	Calcareous arg.

TABLE XXIII.—LIST OF DISTRICTS CHARACTERIZED BY ALKALINE ROCK-TYPES: WITH NOTES ON THE NATURE OF COUNTRY ROCKS.—*Continued*

Region	Alkaline eruptives	Carbonate rocks cut by alkaline eruptives
NEW JERSEY.		
Beemerville.	Nephelite syenite.	Thick limestone.
Brookville.	Ditto.	Li. adjacent.
Franklin Furnace.	Ouachitite.	Crystalline li.
VIRGINIA.		
Augusta County.	Nephelite syenite, teschenite.	Paleozoic li. and sh.
NEW YORK.		
Cortlandt.	Sodalite syenite, trachyte, syenite.	Thick li.; basic schists.
Lake Champlain.	Bostonite, monchiquite, fourchite, camptonite.	Pre-Cambrian and Paleozoic li.
Lyon Mt.	Bostonite, trachyte.	(Laurentian gneiss!)
MASSACHUSETTS.		
Essex County.	Foyaite, essexite, syenite, etc.	Lower Paleozoic li. and calcareous arg.
NEW HAMPSHIRE.		
Red Hill.	Foyaite, bostonite, camptonite, paisanite, umptekite, etc.	(Gneiss and granite!)
Belknap Mts.	Essexite, syenite, camptonite.	(Basic schists.)
VERMONT.		
Ascutney Mt.	Essexite, alkaline syenites, etc.	Paleozoic li. and calcareous schists.
MAINE.		
Aroostook County.	Teschenite, syenite, trachyte.	Paleozoic li., sh., ss.

TABLE XXIII.—LIST OF DISTRICTS CHARACTERIZED BY ALKALINE ROCK-TYPES: WITH NOTES ON THE NATURE OF COUNTRY ROCKS.—*Continued*

Region	Alkaline eruptives	Carbonate rocks cut by alkaline eruptives
MEXICO.		
San Jose.	Nephelite syenite, camptonite, syenite, tinguaite.	Thick Cretaceous li.
NICARAGUA.		
Uani.	Phonolite.	?
COSTA RICA.		
"Eastern part".	Theralite.	Tertiary (and older?) li.
Culebra Bay.	Phonolite.	?
Nicoya Peninsula.	Teschenite.	Thick li.
Avangares Dist.	Limburgite.	Tertiary li.
	SOUTH AMERICA	
BRAZIL.		
Sao Paulo.	Foyaite, jacupirangite, teschenite, nephelinite, augitite, limburgite, syenite, etc.	Paleozoic li. in sl.; (pre-Cambrian li. ?).
Caldas.	Foyaite, phonolite, leucitophyre.	?
PARAGUAY.		
(Locality?)	Phonolite, limburgite.	?
ARGENTINE.		
Salta Province.	Essexite, trachydolerite.	?
San Juan Province.	Essexite, nephelite basalt, limburgite, trachyte-tephrite.	Paleozoic (?) and Jurassic li.
PATAGONIA.		
Sub-andine region.	Essexite, trachydolerite, analcitic essexite, camptonite.	Li., calcareous arg., phyllite.

TABLE XXIII.—LIST OF DISTRICTS CHARACTERIZED BY ALKALINE ROCK-TYPES: WITH NOTES ON THE NATURE OF COUNTRY ROCKS.—*Continued*

Region	Alkaline eruptives	Carbonate rocks cut by alkaline eruptives
	EUROPE	
SCOTLAND.		
Loch Borolan.	Nephelite syenite, borolanite, pulaskite.	Paleozoic li. and dolomite.
Inchcolm Island.	Teschenite, picrite.	Paleozoic calcareous sediments.
Lugar.	Teschenite.	Paleozoic li., etc.
Hebrides.	Monchiquite, crinanite, etc.	Torridonian li., etc.
Eildon and Garlton Hills.	Phonolite.	Paleozoic li. (probably).
Kilpatrick Hills.	Mugearite, trachydolerite, limburgite, etc.	Paleozoic li., etc.
ENGLAND AND WALES.		
Lurcombe, Devon.	Teschenite.	Thick Devonian li.
Golden Hill, Monmouth.	Monchiquite.	Old Red marls, etc.
IRELAND.		
Rathjordan.	Analcite basalt.	?
FRANCE.		
Velay.	Phonolite, trachyte.	Tertiary marls, li.
MontDore.	Phonolite, tephrite, trachyte.	? (Crystalline complex).
Cantal.	Phonolite, trachyte.	Li. in crystalline basement complex; Oligocene li., marl.
Pouzac.	Nephelite syenite, bostonite, etc.	Mesozoic li.
Fitou (Aude).	Nephelite syenite.	"Mesozoic sediments."

TABLE XXIII.—LIST OF DISTRICTS CHARACTERIZED BY ALKALINE ROCK-TYPES: WITH NOTES ON THE NATURE OF COUNTRY ROCKS.—*Continued*

Region	Alkaline eruptives	Carbonate rocks cut by alkaline eruptives
SPAIN.		
Fortuna.	Fortunite, jumillite, trachyte.	Tertiary marls; Cretaceous li.
Catalonia.	Nephelite basanite, limburgite.	Tertiary and older li.
PORTUGAL.		
Serra de Monchique.	Nephelite syenite, monchiquite, camptonite, bostonite, tinguaite, pulaskite.	Pre-Culm li.; Jurassic li. in roof(?).
Cesimba, Fonte da Bica, etc.	Teschenite.	Cretaceous and older li.
Cevadaes.	Nephelite gneiss.	Schists, including lime-silicate rocks.
ITALY.		
Thirteen districts as under: Vulsinian, Ciminian, Sabatinian, Latian, Hernican, Auruncan, Campanian, Vesbian, Phlegrean, Mte. Vulture, Tuscan, Venetian, Apulian (named by H. S. Washington).	Leucite tephrite, trachyte, phonolite, leucite basanite, leucitite, melilitic leucitite, latite, etc.	Thick Mesozoic and Tertiary li. and dolomite.
GERMANY.		
Kaiserstuhl, Baden.	Phonolite, nephelite basalt, limburgite, leucite basalt, tephrite, leucite, phonolite, etc.	Mesozoic and Tertiary li., dolomites, and marls.
Haardt Mountains, Elsass; Mainz basin, etc.	Limburgite.	Muschelkalk and older and younger li.

TABLE XXIII.—LIST OF DISTRICTS CHARACTERIZED BY ALKALINE ROCK-TYPES: WITH NOTES ON THE NATURE OF COUNTRY ROCKS.—*Continued*

Region	Alkaline eruptives	Carbonate rocks cut by alkaline eruptives
Katzênbuckel, Baden.	Nephelite basalt, shonkinite, theralite, etc.	Mesozoic li. and dolomites.
Hegau, Baden.	Nephelite basalt, melilite-nephelite basalt, melilite basalt, phonolite.	Ditto.
Swabian Alp.	Melilite basalt.	Ditto.
Siebengebirge.	Essexite, trachydolerite, monchiquite, trachyte, etc.	Devonian calcareous graywacke and older sediments.
Eifel.	Leucite basalt, nephelite basalt (bearing melilite), phonolite.	Ditto.
Vordereifel.	Ditto.	Ditto.
Westerwald.	Phonolite.	Devonian li. adjacent.
Weser-Werra-Fulda District.	Nephelite basalt, leucite basalt, melilitic nephelite basalts.	Mesozoic li. and marls and Paleozoic calcareous sediments.
Rhön.	Phonolite, trachyte, nephelite basalt (often leucitic), limburgites, basanites.	Ditto.
Vogelsberg.	Nephelite basalt, phonolite, trachyte.	Ditto.
Saxony, many localities.	Phonolite, nephelite basalt.	(Lausitz granite.)
AUSTRIA.		
Predazzo, Tyrol.	Nephelite syenite, essexite, shonkinite, theralite, monzonite, tinguaite, camptonite, monchiquite, etc.	Triassic dolomite. (Also older li.?)
Monzoni, Tyrol.	Monzonite, essexite, alkaline syenites, tinguaites, etc.	Ditto.
Duppau Hills, Bohemia.	Phonolite, leucite basalt, leucitite, leucite tephrite, leucite basanite, nephelite basalt,	Tertiary marls and calcareous tuffs.

TABLE XXIII.—LIST OF DISTRICTS CHARACTERIZED BY ALKALINE ROCK-TYPES: WITH NOTES ON THE NATURE OF COUNTRY ROCKS.—*Continued*

Region	Alkaline eruptives	Carbonate rocks cut by alkaline eruptives
Duppau Hills, Bohemia.—*Con.*	nephelinite, nephelite tephrite, limburgite, augitite, nephelite syenite, augite syenite, theralite.	
Mittelgebirge, Bohemia.	Phonolite, tephrite, essexite, sodalite syenite, trachyte, nephelite basalt, limburgite, melilite basalt.	Mesozoic and Paleozoic li. and marls.
Steiermark, Austria.	Nephelite basanite, nephelinite, nephelite basalt.	Tertiary Mesozoic (and older?) li. and marls.
Ditro, Hungary.	Nephelite syenite (many phases).	Li. in phyllitic terrane. (Also younger limestones?)
Teschen.	Teschenite.	Li. and marly "Schiefer."
Medves Mts.	Nephelite basanite.	?
RUSSIA.		
Caucasus.	Teschenite.	Mesozoic li. and argillite.
Azof.	Mariupolite, orthophyre, grorudite, pyroxenite, etc.	? Paleozoic (Devonian and Carboniferous) li. ?
Miask and Kussa.	Nephelite syenite, cancrinite syenite, corundum syenite.	Crystalline li. adjacent.
Kuusamo Parish, Finland.	Nephelite syenite, ijolite.	?
Kuolajärvi, Finland.	Cancrinite syenite.	Limestone.
Kola Peninsula.	Nephelite syenite, urtite, lujavrite, umptekite, chibinite, etc.	Devonian (?) marly clay-slates. (Also li. ?)
Ahnevaara.	Essexite, syenite.	?
SWEDEN.		
Alnö.	Foyaite, ijolite, jacupirangitic phases, bostonite, alnöite, etc.	Crystalline li.

TABLE XXIII.—LIST OF DISTRICTS CHARACTERIZED BY ALKALINE ROCK-TYPES: WITH NOTES ON THE NATURE OF COUNTRY ROCKS.—*Continued*

Region	Alkaline eruptives	Carbonate rocks cut by alkaline eruptives
Elfdalen.	Cancrinite tinguaite.	Paleozoic li.
NORWAY.		
Gran.	Essexite, bostonite, camptonite.	Paleozoic li., including Etage 1 to 3.
Christiania.	Essexites, akerites, laurvikites, monzonites, laurdalite, pulaskite, nordmarkite, ekerite, camptonite, rhomb-porphyry, etc.	Paleozoic li. (and arg.).
	ASIA	
Smyrna.	Leucite tephrite.[a]	Li., marl.
Tschamly Bei.	Leucite basanite.	Li.
Kesmek-Köpru.	Nephelite dolerite.	Marls.
Trebizond.	Leucotephrite.	Eocene li. and Cretaceous sediments.
Kula.	Kulaite (trachydolerite), leucite kulaite.	Tertiary (and older?) li.
Troad.	Nephelite basalt.	Thick Cretaceous and Tertiary li.
Northern Syria.	Nephelite basanite, limburgite.	Cretaceous li.
Aden Peninsula.	Phonolite, trachyte.	Cretaceous li.?
Cahétie Mts., Georgia.	Teschenite, dacite, etc.	Cretaceous li.; Tertiary marls and clays.
Upper Zarafshan (Turkestan).	Nephelite syenite, sodalite syenite.	Li. and calcareous schist.
Madras, India.	Nephelite syenite, syenite, corundum syenite.	? (Li. in complex?).
Rajputana, India.	Nephelite and sodalite syenites	? (Li. in complex?).
Coimbatore, India.	Nephelite syenite.	? (Li. in complex?).

TABLE XXIII.—LIST OF DISTRICTS CHARACTERIZED BY ALKALINE ROCK-TYPES: WITH NOTES ON THE NATURE OF COUNTRY ROCKS.—*Continued*

Region	Alkaline eruptives	Carbonate rocks cut by alkaline eruptives
Mount Girnar, India.	Nephelite syenite, monchiquite.	?
Manchuria.	Nephelite basalt.	? (Cambrian li. in region).
Yenisei, Siberia.	Nephelite syenite, leucite syenite porphyry, camptonite, etc.	Thick, extensive li., with dolomite and slate.
"Ostsibirien."	Teschenite.	Li. and dolomite.
Southern China.	Nephelite syenite.	? (Thick, extensive Devonian calcareous terrane in region.)
	AFRICA	
Kamerun, Africa.	Nephelite syenite, phonolite, monzonite, keratophyre, bostonite, camptonite, vogesite, leucitite, etc.	Cretaceous (and older?) li.
Niger-Benué Area, West Africa.	Foyaite.	Li. of unknown age.
Ahaggar, Central Africa.	Phonolite.	?
Aïr, Central Africa.	Phonolite, alkaline trachyte.	Silurian li. (Cretaceous marls ?; other li.?)
Great Rift Valley, East Africa.	Phonolites, comendites, trachytes, kenyites, nephelinites (bearing melilite), borolanite, nephelite basalt, limburgite, tephrite, nephelite basanite, leucite basanite.	? Crystalline li. of gneissic plateau; calcareous sandstone, conglomerate and shales of Paleozoic?
Abyssinia.	Phonolites, tinguaites, grorudite, paisanite, sölvsbergite, etc.	(Thick crystalline li. and dolomites in gneissic plateau; also Jurassic and younger li.)
Potchefstroom.	Nephelite syenite.	Dolomite, sl., etc.
Bushveldt, Transvaal.	Nephelite syenite, monchiquite, camptonite, bostonite, etc.	The Great Dolomite.
Marico, Transvaal	Nephelite syenites.	Ditto.

TABLE XXIII.—LIST OF DISTRICTS CHARACTERIZED BY ALKALINE ROCK-TYPES: WITH NOTES ON THE NATURE OF COUNTRY ROCKS.—*Continued*

Region	Alkaline eruptives	Carbonate rocks cut by alkaline eruptives
Spiegel River, Cape Province.	Melilite basalt.	Li., calcareous sh. and schist.
Sutherland, Cape Province.	Ditto.	Ditto.
Namqualand.	Nephelite basalt, melilite-nephelite basalt.	Li. in gneissic terrane and in Malmesbury beds.
	AUSTRALIA	
NEW SOUTH WALES.		
Warrumbungle Mts.	Phonolite, trachydolerite, comendite, melilite basalt (bearing corundum), trachyte, etc.	Mesozoic calcareous sh.; Paleozoic li., etc.
Nandewar Mts.	Nephelite syenite, bostonite, syenite, trachyte.	Paleozoic li. and calcareous sh., etc.
Canobolas Mts.	Melilite basalt, comendite, phonolitic trachyte.	Ditto.
Dubbo.	Nephelite syenite, phonolite, trachyte.	Ditto (probably).
Mittagong.	Essexite, trachyte, syenite.	Paleozoic calcareous sh. (and li. probably).
Mt. Prospect.	Essexite.	Triassic sh. (probably Paleozoic li.).
Kiama-Jamberoo.	Nephelite syenite, tinguaite, monchiquite, etc.	Permo-Carboniferous sh. (probably Paleozoic li.).
Barrigan.	Tinguaite.	?
Capertee Valley.	Nephelite basalt.	Permo-Carboniferous sh. (probably Paleozoic li.).
Kosciusko.	Phonolite.	?
QUEENSLAND.		
Glass House Mts.	Pantellerite, comendite, alkaline trachyte, keratophyre, bostonite.	Mesozoic sh., etc. (Paleozoic li.?)
Maroochy-Cooran	Ditto.	Ditto.

TABLE XXIII.—LIST OF DISTRICTS CHARACTERIZED BY ALKALINE ROCK-TYPES: WITH NOTES ON THE NATURE OF COUNTRY ROCKS.—*Continued*

Region	Alkaline eruptives	Carbonate rocks cut by alkaline eruptives
Mt. Flinders-Fassifern.	Phonolite, pantellerite, comendite.	Highly calcareous Mesozoic sediments.
East Moreton.	Analcite dolerite, comendite, sölvsbergite, pantellerite, monzonite, trachyte.	Mesozoic and Paleozoic arg. (and li?).
VICTORIA.		
Mt. Macedon.	Sölvsbergite, alkaline trachyte, macedonite, limburgite, anorthoclase basalt, etc.	(Ordovician sh.)
SOUTH AUSTRALIA.		
Harden.	Leucite basalt.	(Silurian sl.)
	ANTARCTICA	
Ross Archipelago.	Phonolite, trachydolerite, kenyite, leucite kenyite, limburgite, camptonite, trachyte.	? (Thick li. in basement terrane.)
	ISLANDS	
Regatta Point (Tasmania.)	Nephelite syenite, essexite, jacupirangite, sölvsbergite, tinguaite, nephelinite, syenite, melilite basalt, limburgite, etc.	Paleozoic li.
Hobart (Tasmania)	Nephelite basalt.	?
Shannon Tier (Tasmania).	Melilite-nephelite basalt, eudialyte-nephelite basalt.	?
Dunedin (New Zealand).	Foyaite, trachydolerite, teschenite, phonolite, tinguaite, leucitophyre, nephelite basanite, melilite basanite, trachyte, etc.	Tertiary li. and calcareous sediments. (Older li?)
Campbell Island.	Phonolite, melilite basalt.	Miocene li.
Auckland Islands.	Alkaline trachyte.	?
Possession Island.	Phonolite.	?

TABLE XXIII.—LIST OF DISTRICTS CHARACTERIZED BY ALKALINE ROCK-TYPES: WITH NOTES ON THE NATURE OF COUNTRY ROCKS.—*Continued*

Region	Alkaline eruptives	Carbonate rocks cut by alkaline eruptives
Juan Fernandez.	Phonolitic trachyte.	?
Ponape Island (Carolines).	Nephelite basalt.	?
Raiatea Island (Society Group).	Phonolite.	?
Viti (Fiji).	Foyaite.	? (Crystalline li. in island basement.)
Tahiti.	Nephelite syenite, tinguaite, monchiquite, phonolite, essexite, monzonite, picrite.	?
Savaii, Upolu, and other islands (Samoan Group).	Trachydolerite, phonolite, nephelite basanite.	?
Java.	Tephrite, leucite basalt, leucitite.	Li., marl.
Loh oelo (Java).	Theralite-diabase.	Calcareous Eocene and Cretaceous sediments.
Western Celebes.	Leucite basalt.	?
Northern Celebes.	Phonolite.	?
Saleyer (Moluccas)	Nephelite tephrite.	?
Buru Island (Indo-Australian Archipelago).	Melilite basalt.	?
Timor.	Foyaite.	Tertiary and Paleozoic li.
Hawaii.	Phonolitic trachyte, trachydolerite, etc.	?
Maui.	Melilite-nephelite basalt.	?
Oahu.	Nephelite basalt, melilite-nephelite basalt.	?

TABLE XXIII.—LIST OF DISTRICTS CHARACTERIZED BY ALKALINE ROCK-TYPES: WITH NOTES ON THE NATURE OF COUNTRY ROCKS.—*Continued*

Region	Alkaline eruptives	Carbonate rocks cut by alkaline eruptives
Dependent Isles of Taiwan (off Japan).	Analcite basalt.	?
Réunion.	Essexitic gabbro, mugearite, phonolitic trachyte, syenite.	?
Madagascar.	Nephelite syenite, nephelite basalt, phonolite, trachyte, limburgite, camptonite, melilite basalt, laurvikite, monzonite, augitite, essexite.	Jurassic li. and marls. (Older li.?)
Trinidad, South Atlantic.	Phonolite, nephelinite, limburgite.	? Coral reefs?
Heard.	Nephelite basalt, limburgite.	? (Li. blocks in crater).
Kerguelen.	Phonolite, trachyte, limburgite.	? (Roth found dolomite here.)
Nightingale.	Phonolite.	?
Fernando Noronha	Phonolite.	?
Cabo Frio (Brazil).	Foyaite, pulaskite, essexite, tinguaite, monchiquite.	?
Saint Helena.	Phonolite.	?
Ascension.	Alkaline trachyte.	?
Sao Thomé.	Phonolite, trachyte, limburgite.	?
Los Islands (Africa).	Nephelite syenite.	?
Selvagem Grande (Salvages Islands).	Phonolite, nephelinite, limburgite.	? (Li. "dikes" in island.)
Madeira.	Essexite, trachydolerite, alkaline trachyte, etc.	?
Azores.	Phonolite, trachyte, etc.	?

TABLE XXIII.—LIST OF DISTRICTS CHARACTERIZED BY ALKALINE ROCK-TYPES: WITH NOTES ON THE NATURE OF COUNTRY ROCKS.—*Continued*

Region	Alkaline eruptives	Carbonate rocks cut by alkaline eruptives
Canary Islands.	Phonolite, trachydolerite, basanite, nephelinite, limburgite, tephrite, essexite, nephelite syenite, monzonite, camptonite, bostonite, gautëite, limburgite, nordmarkite, pulaskite, akerite.	? Mesozoic and Paleozoic li. beneath volcanoes? Li. on Fuerteventura. (Continuation of Atlas Mountains li. formations?)
Cape Verde Islands.	Foyaite, syenite, phonolite, leucitite, tephrite, basanite, nephelinite, nephelite basalt, limburgite, etc.	? Li. of Mayo, S. Thiago, and Praya islands?
Julianehaab, Greenland.	Foyaite, sodalite syenite, lujavrite, etc.	? (Pre-Cambrian granite and Paleozoic sandstone.)
Columbretes (Mediterranean).	Phonolite, trachyte.	?
Monte Ferru, Sardinia.	Phonolite, trachydolerite, leucite basanite, leucite basalt.	Tertiary li. and marls (older li.?).
Pantelleria.	Phonolite, trachydolerite.	? (Tertiary and Mesozoic li.?).
Lipari Islands.	Leucite basanite, trachydolerite, etc.	? (Tertiary and Mesozoic li. ?).
Etna, Sicily.	Leucitophyre, trachydoleritic basalt.	Tertiary and Mesozoic li.

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Date Due

QE 461 D2

Daly, Reginald A.

AUTHOR

Igneous rocks and their origin.

TITLE

DATE DUE	BORROWER'S NAME
MAY 20 '62	D. R. Waldbaum
[illegible]	B. Raymahashay
2 '66	J S Rann 26 May 1966
[illegible]	
5 1972	[illegible]

PRINTED IN U.S.A. 23-521-001